understanding UHF equipment

by John D. Lenk

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UNDERSTANDING UHF EQUIPMENT • LENK FOULSHAM-SAMS

Encountering ultrahigh-frequency equipment for the first time can be a bewildering experience for the student or beginning technician. After having acquainted himself somewhat with the "normal" electronic gear and components used at lower frequencies, he is suddenly confronted with such an array of "plumbing" and other seemingly nonelectronic paraphernalia that he truly finds himself in a quandary. Nothing seems recognizable for what it really is! This book should prove to be most valuable for those who find themselves in such a state of confusion.

The first chapter contains answers, presented in a brief and straightforward manner, to a series of questions most often asked of instructors in the uhf field. Other chapters contain detailed information on specific items of uhf components, circuits, and equipment. Throughout the book, emphasis is placed on fundamentals and basic features. In addition, comparisons between uhf and lower-frequency equipment are given so that the exact function of uhf components and circuits can be more easily understood.

In the last chapter, specific items of test equipment and various techniques that are unique to uhf and microwave operation are described and illustrated.

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UNDERSTANDING
UHF EQUIPMENT

UNDERSTANDING UHF EQUIPMENT

by

JOHN D. LENK

With a specially written chapter for the guidance of the English reader by W. Oliver (G3XT)

FOULSHAM-SAMS

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It is essential that the English reader should read this chapter.

The frequency of radio waves (inversely proportional to their length) may be said to range from very low to extremely high.

The range in terms of Hertz or cycles per second is enormous (see page 8), but where radio waves are concerned, their length or frequency has a significance far deeper than that of a mere measurement as such.

Actual behaviour and propagation characteristics of radio waves differ quite drastically from one portion of the spectrum to another. In other words, low-frequency waves travel differently from high-frequency ones, and these again differ in their properties from ultra-high-frequency (uhf) waves.

This book is concerned, as its title states, with the ultra-high-frequency portion of the spectrum, broadly defined as extending from about 300 to about 3,000 Mhz. But of course such divisions of the spectrum are more or less arbitrary and in reality one portion merges into another without any very sharp line of demarcation.

If one switches transmission or reception from, say, the medium waveband to the short waveband (or hf part of the spectrum), one immediately encounters problems that are not evident on the lower frequencies. But along with the snags one also finds great advantages. For example, worldwide communication even on fairly low power is readily possible on the short waves but virtually impossible on the medium waves.

Going up still higher in frequency (or down lower in wavelength), a crop of fresh problems arise which are more or less peculiar to the ultra-high frequency region. These problems, affecting the design and operation of uhf equipment, are dealt with in this book. Offsetting the problems, some advantages accrue (page 8).

The portions of transmitting and receiving circuits which have to be specially designed for uhf work are, logically enough, those parts which are, so to speak, "nearest" to the actual waves. In other words, the later stages of a transmitter, especially the final

or output stage; the aerial tuning circuits; and the transmitting aerial itself—these are the crucial items at the sending location.

At the receiving location, the order is reversed; the receiving aerial; the aerial tuning circuits; and the first stage or "front end" of the set are the items that need special attention to design in a uhf receiving circuit.

Individual chapters of the book have therefore been devoted to uhf aerials (antennas), transmission lines, tuned circuits and so on. Other chapters deal with design problems in uhf converters, uhf test equipment and measuring gear.

Various methods of frequency-multiplying are used to arrive at a satisfactory output with a transmitter designed to operate on uhf. A device which has become increasingly popular of late in this application is the varactor. This is a very small and simple component with a good many different uses, of which frequency multiplying is only one.

A varactor is a special type of semiconductor diode, the internal capacitance of which can be varied within limits by varying the voltage applied to the device. If you want to read more about the various specialised uses of varactors, a very useful book on the subject in the Foulsham-Sams series is "ABC's of Varactors" by Rufus P. Turner.

Several of the leading manufacturers of solid-state devices are currently producing varactors. As regards retail supplies, various mail-order and other radio firms can supply certain types of varactors from stock at the time of writing. For example, some inexpensive varactors are currently available from L.S.T. Components of 23 New Road, Brentwood, Essex.

Among the advantages of a varactor are its small size, extreme simplicity, very reasonable cost and the fact that it does not need a power supply in the way that many other devices do.

Regarding the acorn valve type 955 featured in a circuit on page 97 (Fig.7-11), this valve which has proved its efficiency over many years is an ideal one for special applications such as the oscillator circuit shown in that diagram, and is still available at the time of writing from various mail-order firms, including P.C. Radio Ltd., 170 Goldhawk Road, London, W.12; and Z. and I. Aero Services Ltd., 44a Westbourne Grove, London, W. 2. A special type of valveholder is required.

The 6AM4 featured in a uhf mixer stage forming the subject of Fig. 9-9 is currently listed by the Bentley Acoustic Corporation Ltd., 38 Chalcot Road, Chalk Farm, London, N.W. 1 for callers and 47 Norfolk Road, Littlehampton, Sussex, for mail orders.

Pinnacle Electronics Ltd., Achilles Street, New Cross, London, S.E. 14, is a most useful source of supply for "difficult" or special valves not easily obtainable elsewhere, as well as for more ordinary types. Hard-to-get American tubes are one of the specialities of this firm at the time of writing.

"Difficult" and specialised types of transistors, diodes and other solid-state devices are obtainable from M. R. Clifford and Company, 209a Monument Road, Edgbaston, Birmingham 16.

Availability of stock alters as time goes on, and even addresses of firms are liable to change, so it is most essential to verify these details from the latest information such as the advertisements of the various mail-order and other suppliers which will be found in current issues of radio technical journals such as "Wireless World", "Short Wave Magazine", "Radio Constructor", "Radio Society of Great Britain Bulletin", "Practical Electronics", "Practical Wireless", and so on.

Preface

The ultrahigh frequency range of the radio spectrum is now being used extensively by many communications services that previously utilized only the lower-frequency bands. The reason is simply that the lower-frequency bands are overcrowded, and only in the uhf and higher-frequency bands are there sufficient channels available for expansion. The uhf bands will probably remain the center of expansion for some time, since techniques and equipment for utilizing the higher-frequency bands (superhigh frequency, or shf) have not as yet been developed to the point where reliable, long-range communications in television, telemetry, etc., is possible.

The use of ultrahigh frequency equipment in two-way voice communications, missile guidance systems, satellite communications, and telemetering has increased tremendously in the last several years. In addition, in April, 1964, the FCC required that all future television receivers produced must provide for the reception of uhf stations. Consequently, any technician, whether he works in television, communications, or industry, should have a thorough understanding of the basic features of uhf equipment. A study of this book will provide such an understanding.

The material in this book is intended to serve a dual purpose. First, it provides the working technician with a handy reference book of valuable, basic information when he encounters some aspect of the uhf field for the first time. Second, the book can be used as part of a training course in uhf at the trade-school or technical-institute level. All phases of uhf equipment are covered, with emphasis placed on fundamentals and basic features. Throughout the book, the differences between uhf and lower-frequency equipment are described and illustrated.

JOHN D. LENK

To my wife Irene and daughter Karen

Contents

1

Introduction to UHF

In many respects, uhf circuitry is similar to the circuitry used at lower frequencies. In fact, many uhf transmitters and receivers are identical to lower-frequency units except for the operation of one stage. In a transmitter, this is the final output stage. In a receiver, it is the input, or "front end," that makes a uhf unit different from a lower-frequency unit. It is assumed in the following chapters that the reader is familiar with the basic circuits of lower-frequency equipment. Such data will not be covered here, except as it pertains to special characteristics of uhf equipment.

When uhf equipment of any kind is faced for the first time, certain questions arise in the minds of technicians and experimenters. For that reason, much of the information in this chapter is presented in question-and-answer form. These represent the inquiries most often received by instructors in the uhf field. A thorough study of them will give an overall picture of uhf equipment as it stands today. Other chapters contain detailed information on specific types of uhf equipment.

WHAT IS THE UHF BAND?

The uhf band has been arbitrarily established as those frequencies from 300 to 3000 megahertz.* The entire radio-frequency spectrum has been divided into bands. In many cases, these divisions are on an arbitrary basis. In actual practice, the spectrum could be divided on the basis of radio-wave behavior. For example, above 1000 MHz, radio waves take on the properties of light waves. They can be beamed, and will travel in a line-of-sight path.

* Hertz (Hz) = cycles per second.

WHAT IS THE RELATIONSHIP OF THE UHF BAND TO OTHER BANDS?

The following shows the relationship of the various radio bands:

RANGE	BAND
10 to 30 kHz	Very low frequency (vlf)
30 to 300 kHz	Low frequency (lf)
300 to 3000 kHz	Medium frequency (mf)
3 to 30 MHz	High frequency (hf)
30 to 300 MHz	Very high frequency (vhf)
300 to 3000 MHz	Ultrahigh frequency (uhf)
3000 to 30,000 MHz	Superhigh frequency (shf)

WHAT ARE THE ADVANTAGES OF THE UHF BAND?

One of the primary advantages of the uhf band is that it is less crowded than the lower-frequency bands. There are, in addition, several practical advantages to uhf in certain applications.

For example, external noise is much less of a problem at ultrahigh frequencies than it is at lower frequencies. In some cases, the common sources of external or man-made noise do not produce uhf components. In other cases, the uhf noise may be present, but of such low amplitude that it causes little actual interference. Generally, it is easier to shield uhf circuitry from external noise. In most cases, the noise generated within a receiver itself is the only limiting factor to receiver sensitivity.

Uhf antennas may be made smaller and more compact than lower-frequency antennas. Antenna length in any radio system is related to the length of the radio waves. Higher frequencies have shorter wavelengths, and thus require shorter antennas. When wavelengths are very short, it is possible to design a highly efficient directive system, and yet keep the design simple and compact. As an example, a simple "dish," or parabolic, reflector will concentrate uhf signals into a narrow beam.

Since uhf signals normally follow a line-of-sight path, it is relatively simple to predict the transmission range. That is, the range or point beyond which communication is not likely can be calculated. It is then possible to use the same operating frequency in many locations, as long as the locations are separated by a distance greater than the line-of-sight range. With lower-frequency signals, where communication is possible with

reflected or sky waves, operating frequencies must be carefully assigned in order to avoid interference.

Because uhf signals can be concentrated into a narrow beam, it is possible to communicate over a greater range at uhf with less power than would be required at lower frequencies. This does not mean that uhf equipment has a greater operating range than lower-frequency equipment. The opposite is true. It does mean, however, that it is possible to operate over the same limited range, with less power on uhf, if highly directive transmitting and receiving antennas are used.

Uhf is ideally suited for broad-band modulation, since the total bandwidth of the modulating signal is a very small fraction of the operating frequency. Therefore, it is possible to superimpose many individual channels on one carrier. As the amount of information contained in the transmission is increased, the required modulation band increases. For example, assume that it is necessary to transmit the entire audio range (up to about 30 kHz) at an operating frequency of 30 or 300 MHz. At 30 MHz the modulation band would be 0.1 percent of the operating frequency. At 300 MHz the modulation band would be only 0.01 percent.

WHAT IS THE MAJOR DIFFERENCE IN UHF CIRCUITRY?

The resonant circuits of uhf equipment are quite different from those used at lower frequencies. In all but a few cases, the resonant circuits at uhf are formed by transmission lines rather than the conventional coil and capacitor circuits. Therefore, it is essential that the student of uhf have a thorough understanding of transmission-line characteristics.

Another difference is the effect of uhf on common electronic components. For example, the reactance of a capacitor varies inversely with frequency: as the frequency increases, the reactance of a capacitor to a-c decreases. A capacitor that would have 6000 ohms of reactance at 3 MHz will have 60 ohms at 300 MHz, and only 6 ohms at 3000 MHz (almost a dead short). In another example, the reactance of a coil varies directly with frequency: as the frequency increases, so does the reactance of a coil to a-c. A coil that would have a reactance of 3 ohms at 3 MHz will have 300 ohms at 300 MHz, and 3000 ohms at 3000 MHz.

At ultrahigh frequencies, mechanical components assume the characteristics of electrical components. For example, any conductor carrying uhf currents will have some inductance. This

applies to the leads of capacitors, resistors, transistors, and tubes, as well as the wiring between them, etc. Therefore, a conventional capacitor used in uhf circuits can assume the function of a resonant circuit, its leads supplying the necessary inductance. Suppose that such a capacitor were replaced by another capacitor with slightly longer leads. This would change the inductance as well as the resonant frequency of the capacitor. Two bad effects could result: (1) the added inductance could cancel out part of the capacitance, and (2) the capacitor could now resonate at some undesired frequency.

HOW CAN A TRANSMISSION LINE FORM A RESONANT CIRCUIT?

A transmission line is basically two parallel wires (Fig. 1-1). A certain amount of self-inductance is present in a single piece of wire carrying current, because of the magnetic fields set up around the wire. With two parallel wires, there is both self-inductance and mutual inductance, since the magnetic fields from one wire cut across the other wire. A capacitor is formed by any two conductors separated by an insulating medium. Therefore, any transmission line has both inductance and capacitance, which is all that is necessary to form a resonant circuit. At some frequency, the capacitive reactance is equal to the inductive reactance. This is the resonant frequency.

The desired operating frequency is obtained by cutting the transmission line to a specific length. In most cases, the transmission line is cut to one-quarter wavelength at the desired resonant frequency. The transmission line can be tuned by

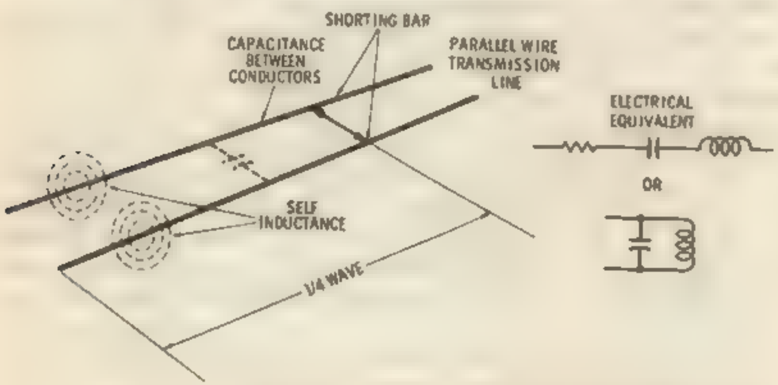


Fig. 1-1. Transmission line as basic resonant circuit.

changing either the inductance or the capacitance, or both. The inductance is usually changed by means of a shorting bar which lengthens or shortens the parallel lines. The capacitance could be changed by varying the distance between the lines. However, for practical reasons, the capacitance is usually changed electrically by a variable capacitor across the lines.

HOW DO UHF SIGNALS AFFECT AN INDUCTOR?

There are two effects on an inductor as the signal frequency is increased. First, the inductive reactance increases directly with the frequency increase. Second, the reactance of the inductor's distributed capacitance decreases. Any coil will have some distributed capacitance (Fig. 1-2). There will be some capaci-

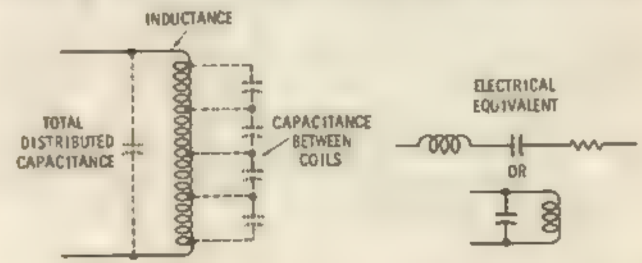


Fig. 1-2. Distributed capacitance in an inductor.

tance between the leads to the inductor, and more capacitance between the turns of wire and from the turns to adjacent grounds. All of these capacitance values are combined to form an overall distributed capacitance.

HOW DO UHF SIGNALS AFFECT A CAPACITOR?

There are two effects on a capacitor as the signal frequency is increased. First, the capacitive reactance decreases directly with the frequency increase. Second, the inductive reactance of the capacitor's leads increases to the point where the capacitor can be considered a resonant circuit (Fig. 1-3). Capacitor leads are conductors, and any conductor has some inductance. Therefore, a capacitor has both inductance and capacitance, and must have a natural resonant frequency. At lower frequencies, the inductance is so small that it can be neglected. At uhf, the inductance becomes a significant value. Also, the capacitive reactance decreases at uhf. When inductive and capacitive reactances are equal in value, the circuit is at reso-

Fig. 1-3. Inductance of capacitor leads becomes significant at uhf.

nance. Therefore, a capacitor has a greater chance of becoming resonant at uhf.

IS THERE SOME WAY IN WHICH THE INDUCTIVE REACTANCE CAN BE MINIMIZED?

There will be some inductive reactance as long as there are any capacitor leads. If the lead length is kept to a minimum, the inductive reactance will also be at a minimum. Special uhf capacitors have been designed where the capacitor and inductor are combined as an integral unit (Fig. 1-4). Here, the same conducting surfaces act as both inductor and capacitor. Since there are no separate capacitor leads, there is no inductive reactance in the capacitor portion.

HOW DO UHF SIGNALS AFFECT A RESISTOR?

Since there is a voltage drop across a resistor, there will be some capacitance. And since there is some inductance in the resistor leads, there will be some inductive reactance. At uhf, the capacitive reactance can become so low that it appears as a short to radio-frequency signals. Likewise, the inductive reactance can appear as a high impedance. Or, the capacitive and inductive reactances can combine to produce a resonance.

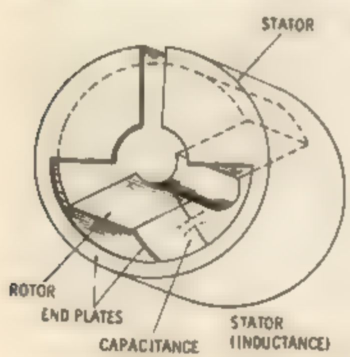


Fig. 1-4. Combined capacitor and inductor for uhf.

If the capacitive reactance remains greater than the d-c resistance, and if the inductive reactance is smaller than the d-c resistance, then the capacitive effect can be neglected and the network becomes equivalent to a resistor and inductor in series.

HOW DO UHF SIGNALS AFFECT MECHANICAL COMPONENTS SUCH AS GROUNDS?

In many uhf circuits, the chassis or enclosure around a particular circuit forms a portion of the circuit. An example of this is the shield around a tuner in uhf television receivers. This shield forms the outer conductor of a resonant-line circuit. There are r-f currents in the shield. This means that there can be a difference in r-f potential or voltage between two ground tie points on the inside of the shield. There can even be a voltage developed across two blobs of solder! If these two solder blobs happen to be one-half wavelength apart, the voltage on one blob will be exactly 180° out of phase with the voltage on the other blob. When the wavelength of the operating frequency becomes comparable to the physical dimension of the mechanical component, the problem becomes significant. At 1000 MHz, a half-wave is only six inches (approximately). Therefore, any points six inches apart on a chassis operating at 1000 MHz could develop into half-wave circuits.

HOW DO UHF SIGNALS AFFECT VACUUM TUBES?

There are several effects, all of which are detrimental. The leads to vacuum-tube electrodes have some inductance. As the frequency increases, so does the inductive reactance; as a result, the leads act as chokes and prevent or reduce r-f current.

There is some capacitance between tube electrodes. As the frequency increases, the reactance of this interelectrode capacitance decreases to the point where there is an r-f short between the electrodes.

The inductance and capacitance of the vacuum-tube electrodes combine with the inductance and capacitance of the external tank circuit. This combination sets an upper frequency limit for operation of the tube as an oscillator or amplifier.

Because of the high speed at which electrons travel between the tube elements (cathode to plate), they are presumed to travel the distance instantly. Actually, there is some measurable transit time. At lower frequencies this transit time is so

short, in relation to the period of one cycle of operation, that its effect is negligible. However, as the frequency increases, the period of one cycle becomes shorter while the transit time remains constant. As the period of the applied frequency approaches about four times the transit time, the tube becomes less efficient and the power capability drops. As the period approaches two times or becomes equal to the transit time, the tube becomes inoperative.

HOW CAN THESE EFFECTS ON VACUUM TUBES BE OVERCOME?

There are several methods. However, each method involves some compromise. The obvious method is to reduce the tube size. This shortens the electrode leads (minimizing inductance), reduces the spacing between electrodes (minimizing capacitance), and reduces the transit time.

However, smaller tubes do not have the power capabilities of larger tubes. Close spacing between electrodes limits the use of high voltages. Smaller plates limit the amount of dissipation possible. Smaller tubes are more easily damaged since their contacts must be made delicate.

Several special-purpose tubes have been developed for use with uhf circuits. These include the acorn and lighthouse tubes, which are discused in later chapters.

HOW DO UHF SIGNALS AFFECT CIRCUIT WIRING?

As the frequency increases, electrical currents passing through a conductor tend to travel on or near the surface of the conductor rather than through the center. This is known as "skin effect." The resistance of a conductor depends on the area of the conductor—the greater the area, the lower the resistance. Although there is no physical change in the area of a conductor at any frequency, the used area decreases as the frequency increases. Consequently, the resistance of a wire increases with frequency. A length of wire that has only a fraction of an ohm of resistance at low frequencies or d-c will have several ohms of resistance at ultrahigh frequencies.

CAN TRANSISTORS BE USED IN UHF?

Older uhf equipment used vacuum tubes almost exclusively, because there was a lack of inexpensive transistors that would

operate satisfactorily in the uhf range. Actually, there have been a number of suitable uhf transistors for some time, but their cost was too high to permit use in commercial equipment. In present-day equipment, such as uhf tv sets, transistors are used as often as vacuum tubes. However, the use of transistors above 1000 MHz is still limited primarily to experimental work.

Transistors definitely have an advantage over tubes for uhf use, if they can meet the frequency limits. Transistors have less background noise and a better signal-to-noise ratio, and they usually show a substantial gain when used in the uhf television receiver conversion process. Vacuum tubes usually show a conversion loss.

HOW CAN PRINTED CIRCUITS BE USED TO ADVANTAGE IN UHF?

Printed circuits offer two advantages when used in uhf equipment. First, a minimum lead length is required to interconnect the various elements in the circuit. This minimizes the inductive reactance presented by leads at uhf. Second, since the various circuit elements maintain fixed physical relationships with each other, there is no chance that the movement of parts will change the circuit values. This is very important at uhf since mechanical parts can assume the functions of electrical parts, as previously discussed.

2

UHF Antennas

Uhf antennas have many characteristics and problems in common with antennas used for other frequencies. Many uhf antennas are identical, except for physical length, to those used in the vhf and lower-frequency bands. In fact, except at the high end of the uhf band where radio waves assume the properties of light waves, the basic characteristics of uhf antennas parallel those of any antenna. For that reason, it is essential that the student of uhf understand both antenna characteristics and terminology. These are discussed in the first sections of this chapter. The last sections of the chapter describe typical uhf antennas in current use. The high end of the uhf band (microwave region) is covered in a separate chapter (Chapter 6) since microwave characteristics are considerably different from those of the lower frequencies.

BASIC ANTENNA TERMS AND DEFINITIONS

The following sections describe the principal terms and definitions applicable to antennas.

Dipole Antenna

A dipole antenna has two elements, or legs, as shown in Fig. 2-1. The typical uhf dipole is center-fed and is one-half wavelength long. This is the electrical equivalent of a tuned resonant circuit with a voltage maximum at the dipole ends and a current maximum at the center. The most common use for a dipole antenna in uhf work is as a receiving antenna for uhf tv.

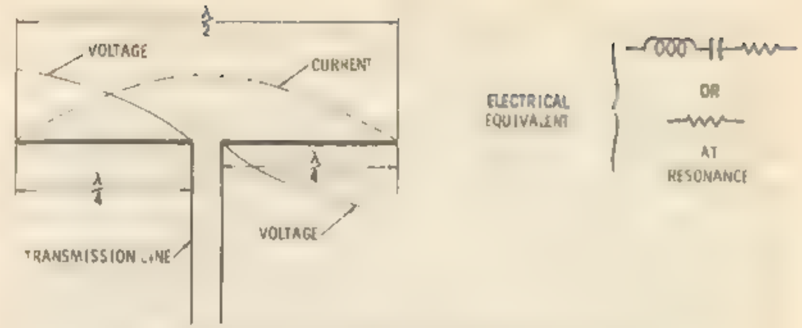


Fig. 2-1. The basic dipole or Hertz antenna.

Monopole Antenna

A monopole antenna has one element, or leg, as shown in Fig. 2-2. The typical uhf monopole is vertical and is one-quarter wavelength long. The current is maximum at the feed or generator end, and the voltage is maximum at the open end. As shown in Fig. 2-2, a vertical monopole antenna is essentially the same as a half-wave dipole that has been cut in half by the ground or other radiating element. Usually, a vertical monopole is used where a nondirective antenna is needed, such as in mobile communications work or in broadcast systems as the transmitting antenna.

Antenna Length

An antenna has wavelength just as do radio waves, since radio waves travel along an antenna in a similar fashion to

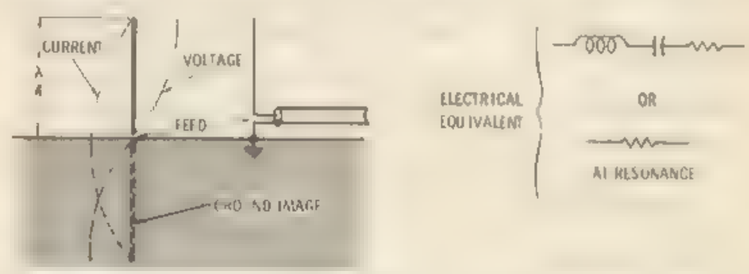


Fig. 2-2. The basic monopole or Marconi antenna.

their movement through space. However, radio waves are slowed down through any conductor (such as the antenna), making a radio wave traveling through space slightly longer than a radio wave (of the same frequency) traveling through

an antenna. In theory, a free-space half-wave is about five or six percent longer than a half-wave antenna.

Antenna Resonance

Electrically speaking, an antenna is equivalent to a resonant circuit. Being a conductor, an antenna has some resistance, some inductance, and some capacitance between itself and nearby objects or the ground. This combination of inductance, capacitance, and resistance produces a resonant circuit. At the resonant frequency, the capacitive and inductive reactances cancel each other, leaving nothing but pure resistance. At any other frequency, the reactances do not cancel completely. Therefore, an antenna at any frequency other than resonance has both reactance and resistance. As with any other resonant circuit, the input impedance depends on the resistance and reactance combination. At resonance, the input impedance of an antenna is equal to the pure resistance, since the reactance is canceled out (in theory). At any other frequency, the input impedance depends on the combination of resistance and reactance.

In the case of a half-wave antenna receiving a signal which has a wavelength longer than the resonant length of the antenna, the input impedance of the antenna is a combination of resistance and capacitive reactance. Under opposite conditions, where the antenna is slightly longer than a half-wave, the input impedance is a combination of resistance and inductive reactance.

In addition to acting as a resonant circuit, an antenna can also be considered as a section of transmission line. A monopole antenna can be considered an open-ended quarter-wave line, while a dipole can be thought of as two open-ended quarter-wave lines.

Antenna Reciprocity

This term simply means that the characteristics of any antenna are virtually the same, whether the antenna is being used for transmission or for reception.

Radiation Resistance

Radiation resistance is a term applied to transmitting antennas. It can be determined by dividing the voltage at the feedpoint by the current at the feedpoint. If it were possible to operate the antenna at exact resonance, the radiation resistance would be pure resistance, without any capacitive or inductive reactance. This is virtually impossible in actual practice.

However, it is possible to tune an antenna close to resonance at a particular frequency. This permits the major portion of the total antenna resistance to be radiation resistance. The higher the radiation resistance in relation to the total resistance (where the pure resistance is high in relation to any reactance), the greater the antenna efficiency.

Antenna Tuning

An antenna can be tuned to a given resonant frequency. The obvious method is to cut or adjust the antenna to a specific length. Another method is to use a tuning stub. Such stubs are particularly useful with half-wave dipoles, and are connected

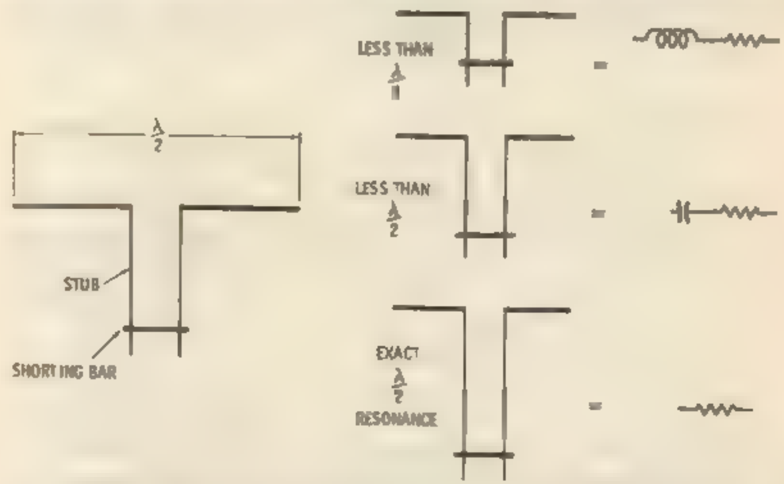


Fig. 2-3. Tuning-stub method of tuning an antenna to resonance.

between the dipole elements as shown in Fig. 2-3. The shorting bar across the stubs permits tuning. When slightly shorter than a quarter-wave, the stub acts as an inductive reactance. As the stub is lengthened to slightly shorter than a half-wave, it acts as a capacitive reactance. If the antenna is too short for a given frequency, a shorted quarter-wave (or slightly less) stub is added. The antenna, being short, is capacitive. The shorted quarter-wave stub, being inductive, tends to offset or cancel any capacitive reactance. Thus, the antenna becomes purely resistive (in theory).

Antenna Impedance

Since an antenna functions as a resonant circuit, it has an impedance. The impedance varies with a number of factors.

One of them is wavelength. For example, the impedance of a typical half-wave dipole is 73 ohms, while a quarter-wave antenna has an impedance of 34 ohms. A full-wave antenna could have an impedance of 8000 to 10,000 ohms. Another factor is the spacing of the antenna elements or feedpoints (in a half-wave dipole). As explained in the next section, increasing the spacing increases the impedance. On antennas with additional parasitic elements, the impedance is reduced as additional elements are added.

Matching Antenna Impedance

When an antenna and the lead-in or transmission line to the antenna are perfectly matched as to impedance, all of the energy or signal will be transferred from the antenna to the lead-

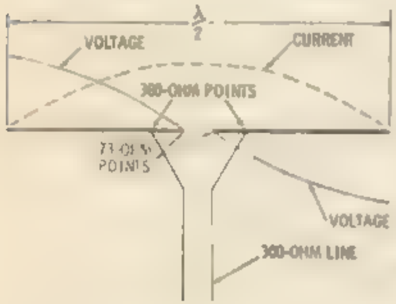


Fig. 2-4. The delta matching system.

in (or vice versa in the case of a transmitting antenna), and there will be no loss. (This is discussed further under "Antenna Vswr.") That is why antennas and transmission lines are usually standardized as to impedance (300 ohms for television twin lead, 73 ohms for coax, etc.).

There are times when it is necessary to match a transmission line of one impedance to an antenna of another impedance. This is usually done at the point where the transmission line feeds into the antenna. Uhf antennas are often fed by coaxial-cable transmission lines, except for uhf television receiving antennas, which usually have a two-wire lead-in or transmission line. Therefore, it is necessary to provide matching systems that are compatible with both coax and two-wire lines. There are two basic types of matching systems: (1) the *delta* match and (2) the *quarter-wave stub* match. The quarter-wave stub can be used with either coax or open-wire lines, while the delta match is usually used with open-wire lines only.

As shown in Fig. 2-4, the delta-match system derives its

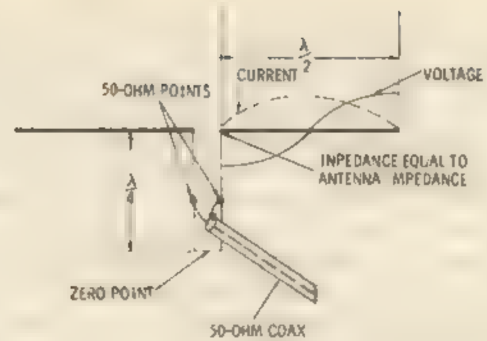


Fig. 2-5. Shorted-stub method of matching low-impedance line to high-impedance antenna.

name from the Greek letter *delta* (Δ). A typical use for the delta system is to match a high impedance line (for example, 300- or 600-ohm open-wire line) to a lower impedance (73-ohm) half-wave dipole. At the usual feedpoint of the dipole, the normal ratio of high current and low voltage produces an impedance of 73 ohms. As the feedpoints are moved out toward the ends of the antenna, the current decreases, while the voltage increases. This changes the ratio so that the impedance is increased. The feedpoints are moved out toward the ends until the impedance is equal to that of the transmission line.

As shown in Figs. 2-5 and 2-6, a quarter-wave section of line can be used to match transmission lines to antennas. In Fig. 2-5, a shorted, quarter-wave section is connected between a coaxial transmission line and a full-wave dipole. At the shorted end of the quarter-wave section, the impedance is zero (zero voltage, maximum current). The coaxial line is con-

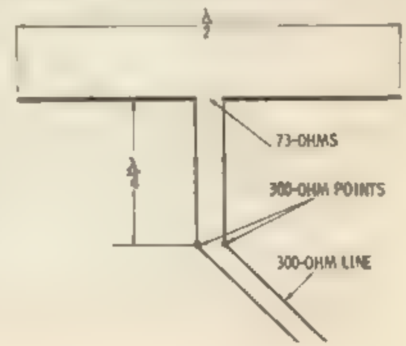


Fig. 2-6. Open-stub method of matching high-impedance line to low-impedance antenna.

nected at the 50-ohm point (to match 50-ohm coax), or at whatever point the impedance matches that of the transmission line. The antenna is connected at the point along the section where the impedance is equal to that of the antenna. With this system, it is possible to move the coax and antenna connection points along the line so that almost any impedance can be matched. In Fig. 2-6, an open-end quarter-wave section is used to match a high-impedance line to a lower-impedance antenna. An open-end quarter-wave section has the same effect as a shorted section, except that the impedance is highest at the generator end and lowest at the load end. In effect, quarter-wave sections act as matching transformers. This action is discussed further in Chapters 4 and 5.

Antenna Feed Systems

Although there are a number of ways in which an antenna can be fed, the feed methods used in uhf can be reduced to *voltage fed* and *current fed*. An antenna is voltage fed if the transmission line is connected to a point of maximum voltage, and is current fed if the transmission line is connected to a point of maximum current. The half-wave dipole and quarter-wave monopole are both current fed. The "flagpole" antennas used in some uhf communications work are voltage fed.

Antenna Polarization and Orientation

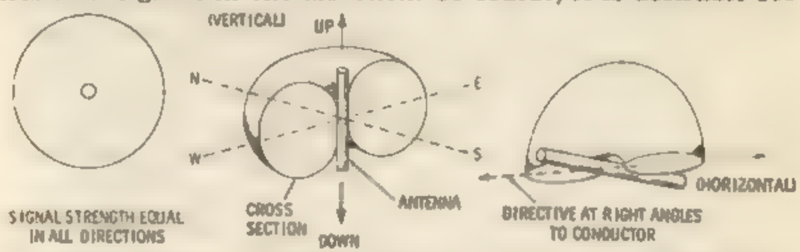
The term "orientation" refers to the direction in which an antenna is mounted relative to ground; that is, vertically or horizontally. Polarization refers to the direction of the electric field produced by an antenna. The terms are not interchangeable, but are interrelated. The polarization of the waves radiated by an antenna (or the direction of the magnetic field) is determined by the orientation of the antenna. For example, vertically polarized waves are produced by a vertical transmitting antenna.

In general, both the transmitting and receiving antennas should be in the same plane. This way, there is maximum pickup of energy by the receiving antenna from the magnetic fields set up by the transmitting antenna, since the receiving antenna is at right angles to the magnetic fields.

It should be noted that the polarization of a radio wave will shift over a long distance. This shift is small at low frequencies, but increases at high frequencies. However, since the communications range in uhf is normally short, both the transmitting and receiving antennas should be in the same plane for best results.

Antenna Directivity

The directivity of a receiving antenna is a measure of the antenna's ability to receive signals in one direction and reject those from other directions. Likewise, the directivity of a transmitting antenna is a measure of the antenna's ability to transmit signals in one direction. Of course, it is desirable for



(A) *Vertical pattern; top view.* (B) *Vertical pattern; cross-sectional view.* (C) *Horizontal pattern; cross-sectional view.*

Fig. 2-7. Vertical and horizontal directivity patterns.

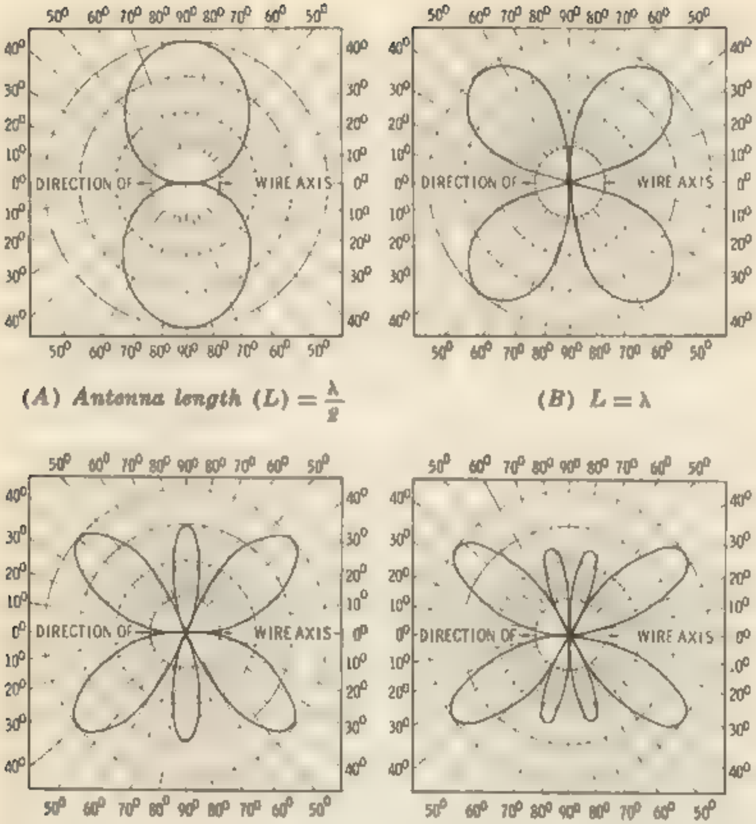
most broadcast and communications transmitting antennas to transmit signals of equal strength in all directions.

Fig. 2-7 shows how a directivity pattern is made up. The normal radiation of a simple vertical antenna is such that the signal strength is equal in all directions (Fig. 2-7A). Actually, the pattern is doughnut shaped (Fig. 2-7B). If this same antenna were made horizontal, the shape would remain the same. However, the antenna would now be directive, with two major lobes on either side (at right angles to the conductor, Fig. 2-7C). This is the typical pattern for a half-wave dipole without any reflector or directive elements.

Fig. 2-8 shows how the directivity pattern of the same half-wave dipole antenna changes when the frequency changes. Additional lobes appear when the frequency is increased. There are four major lobes (four-leaf clover pattern) if the frequency is doubled. In this case, the same antenna is now a full wave. Two additional minor lobes appear if the frequency is tripled. If the antenna is operated at two full wavelengths (frequency quadrupled), there are four major and four minor lobes.

Hertz and Marconi Antennas

A true Hertz antenna is a half-wave (ungrounded) dipole, while a true Marconi antenna is a grounded, quarter-wave antenna. These are shown in Figs. 2-1 and 2-2, respectively. Many



(*A*) *Antenna length* (L) $= \frac{\lambda}{2}$ (*B*) $L = \lambda$

(*C*) $L = \frac{3\lambda}{2}$ (*D*) $L = 2\lambda$

Fig. 2-8. Directivity patterns for the same dipole antenna at four different frequencies of operation.

single-leg (or monopole) antennas used in uhf are incorrectly called Marconi antennas. In reality, they are grounded half-wave antennas (such as the flagpole antenna) or an ungrounded coaxial antenna.

Antenna Vswr

The voltage standing-wave ratio (vswr) of an antenna is actually a measure of the match or mismatch between the antenna and the transmission line or lead-in. When an antenna and the lead-in are perfectly matched as to impedance, all of the energy, or signal, will be transferred from the antenna to the lead-in (or vice versa in the case of a transmitting antenna), and there will be no loss. This is quite rare in actual practice. If it should occur, it will only be at one specific frequency. At any other frequency, there will be a slight mismatch, and some of the energy will be reflected back into the line. This energy or signal will cancel part of the desired signal. If you could measure the voltage along the line, you would find that there were voltage maximums (where the reflected signal is in phase with the desired signal) and voltage minimums (where the reflected signal is out of phase, partially canceling the desired signal). These voltage maximums and minimums are called standing waves, and the ratio of the maximum to the minimum is the standing-wave ratio. A standing-wave ratio of 1:1 means that there are no maximums or minimums (the voltage is constant at any point along the line) and that there is a perfect match between antenna and lead-in. If there is a voltage maximum of, for example, 30 volts and a minimum of 10 volts, the vswr is 1:3 (or 3:1). The reflection of waves and standing waves is discussed further in Chapter 4.

Stacked Antennas and Antenna Arrays

The antenna elements connected to the transmission line are known as *driven* elements.

A receiving antenna is said to be *stacked* when there are two or more driven elements connected together; or when, in effect, two or more antennas are connected together. Each driven element, with its related reflectors and directors (if any), is called a *bay*. Therefore, four dipoles with reflectors, all connected together to form an antenna, would be called a four-bay stacked antenna.

A transmitting antenna is said to be an *array* when it is made up of two or more driven elements. Antenna arrays are usually classified as to the method of feeding the antenna from the transmission line. The three basic classifications or groups include: *end-fire* array, *broadside* array, and *collinear* array.

Broadside Arrays

A broadside array is made up whenever two or more antennas spaced a half-wavelength apart are fed in phase by the same transmission line. As shown in Fig. 2-9, this produces maximum radiation at right angles to a line joining the two or more antenna elements. The half-wave spacing between elements causes a 180° phase shift in the signals from the transmission line. However, since the transmission-line leads are crossed, the elements are fed in phase. To increase directivity, the broadside elements can be stacked. This also increases the

antenna gain. When the elements are stacked one on top of the other, a very sharp vertical pattern is obtained. This prevents energy from traveling up and being lost.

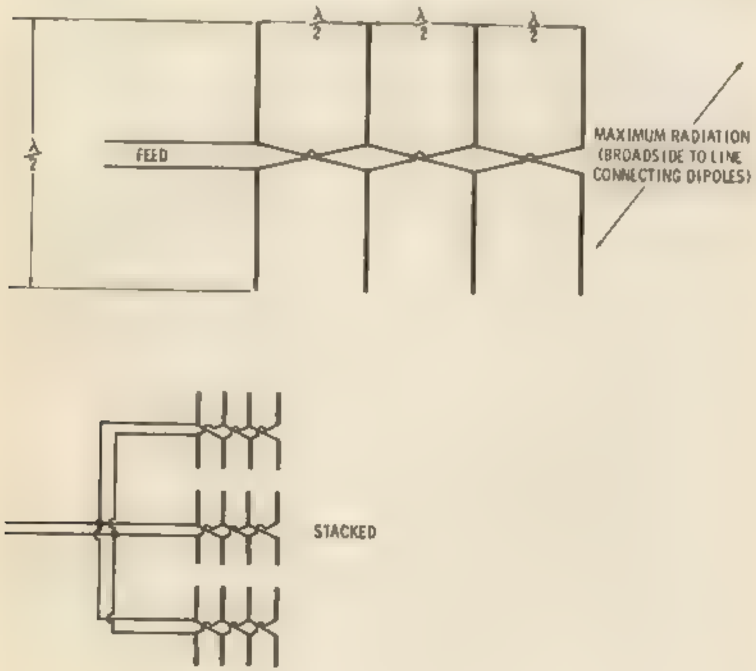


Fig. 2-9. A broadside array.

End-Fire Arrays

An end-fire array is made up whenever two or more antennas, spaced a quarter-wavelength or half-wavelength apart, are fed by the same transmission line, out of phase. As shown in Fig. 2-10, this produces maximum radiation parallel to a line joining the two or more antenna elements. The half-wave spacing between elements causes a 180° phase shift in the signals from the transmission line. This results in a bidirectional radiation pattern. If quarter-wave spacing is used between the elements, a 90° phase shift occurs, and the result is a unidirectional radiation pattern. Like broadside arrays, end-fire arrays can be stacked to increase the gain and sharpen the vertical pattern.

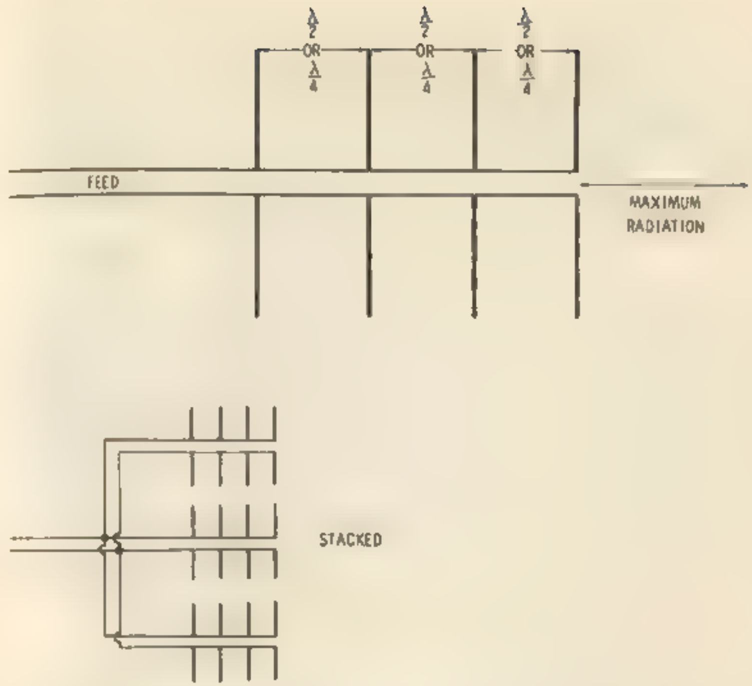


Fig. 2-10. An end-fire array.

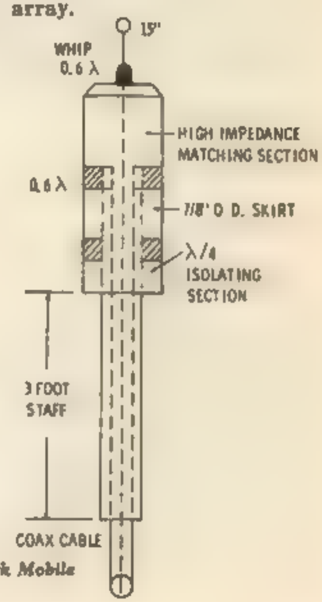


Fig. 2-11. A uhf collinear array for mobile communications.

Courtesy Mark Mobile

Collinear Arrays

A collinear array is made up whenever two half-wave elements are placed end to end and are fed in phase. Radiation from a collinear array is at right angles to the antenna. A typical mobile uhf collinear antenna is shown in Fig. 2-11.

UHF ANTENNA TYPES

There are many types of antennas available for uhf operation. Each has its own particular advantages and disadvantages. Of course, the basic factor in the selection of an antenna is the type of operation. For example, nondirectional antennas are used for communications work, as well as for the transmitting antennas of uhf television. Typical nondirectional antennas in uhf include the various *coaxial* and *ground-plane* antennas. Directional antennas are used for uhf television receiving antennas, as well as for transmitting/receiving antennas in point-to-point uhf work such as television relay links. Typical directional antennas in uhf include the half-wave dipole with some sort of reflector and/or director, or both.

Quarter-Wave Monopole

The quarter-wave monopole shown in Fig. 2-12 differs from the Marconi or vertical antenna previously discussed (see Fig. 2-2) in that it does not require a ground. The enlarged-diameter outer conductor forms an additional element so that the monopole becomes a form of vertical half-wave dipole. Radiation is nondirectional, and the antenna can be mounted at almost any height since the half-wave eliminates the need for a ground.

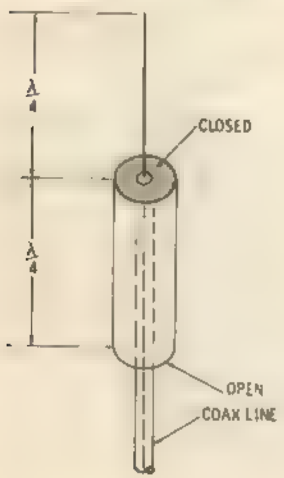
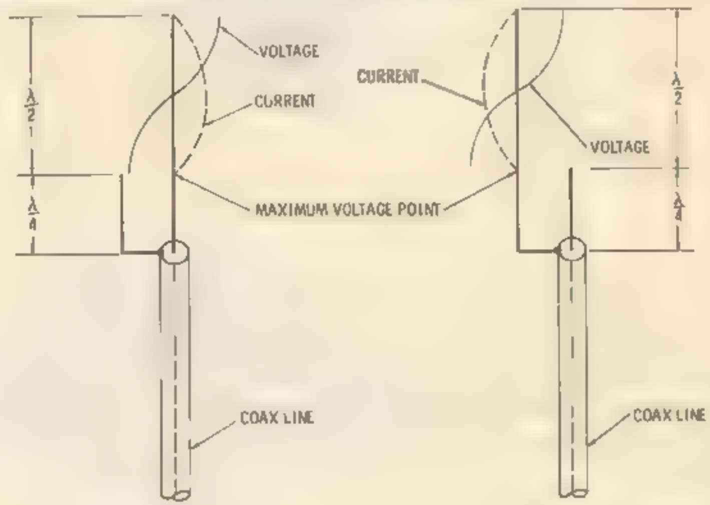


Fig. 2-12. A quarter-wave monopole for uhf.

The half-wave characteristic is obtained by the outer cylinder or sleeve, which is cut to a quarter-wavelength. The coaxial transmission line passes through this sleeve, but is not connected electrically to the sleeve except at the point where the quarter-wave inner conductor starts. Thus, signals are radiated by two quarter-wave elements, center fed by the coaxial transmission line.

Flagpole Antennas

The flagpole antennas shown in Fig. 2-13 are also fed by a coaxial transmission line and have an effective half-wave radiating element. However, the half-wave element is end fed at the point of maximum voltage, rather than center fed at maximum current as is the usual half-wave dipole. This is accomplished by isolating the half-wave antenna from the transmission line by a quarter-wave section. The center conductor of the coaxial transmission line is extended three quarter-wavelengths beyond the outer conductor. A quarter-wave section is connected to the outer conductor and runs parallel to the inner conductor. This quarter-wave section acts as an impedance-matching transformer between the transmission line and the



(*A*) *Theoretical.* (*B*) *Practical.*

Fig. 2-13. Flagpole antennas.

remaining half-wave section of the inner conductor. Both the theoretical and practical flagpole antennas are shown in Fig. 2-13. In practical use, the outer conductor is extended three quarter-wavelengths, while the inner conductor provides the matching quarter-wave transformer section. This provides a direct-current path to ground, should lightning strike the antenna. (Lightning strikes the highest point and will pass through the outer conductor, which is usually grounded).

Ground-Plane Antenna

The ground-plane antenna shown in Fig. 2-14 is fed by a coaxial transmission line and is basically a quarter-wave Marconi antenna. However, a separate ground is not required. The

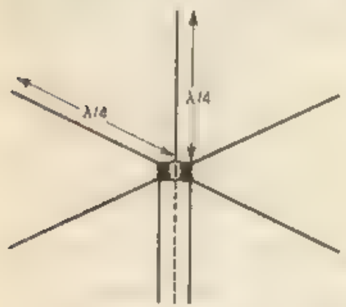


Fig. 2-14. Basic ground-plane antenna.

ground plane is similar to the quarter-wave monopole in this respect. The ground is supplied by crossed horizontal bars which are usually cut to one quarter-wavelength. Normally, the ground plane is nondirectional and is used for general communications work in the uhf band. However, it is possible to add a vertical half-wave reflector to make the antenna directional.

Half-Wave Dipole

The half-wave dipole or Hertz antenna is widely used for reception of uhf television signals, since it can be made highly directive. Also, it can be made to provide high gain over a narrow band of uhf frequencies, or uniform gain over a wide frequency range.

Special Antennas

The length or size of an antenna depends on the operating frequency. The higher the frequency, the smaller the antenna needed. Because uhf antennas are so much smaller, it is possible to manufacture an elaborate, high-gain, multielement

unit at far lower cost. Also, there are antennas which would be quite bulky if designed for lower frequencies, but can be made quite compact for uhf work. The *helical* and the *parabolic* antennas are two examples.

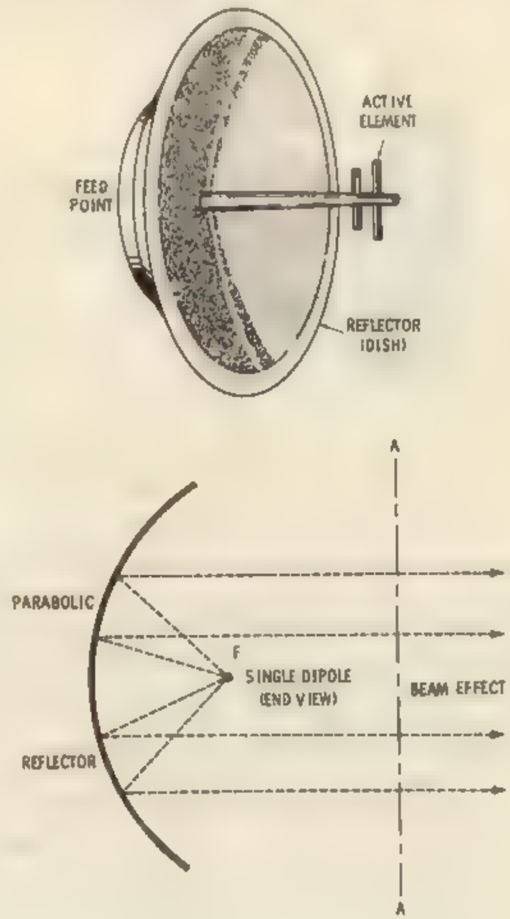


Fig. 2-15. Solid parabolic-reflector antenna.

A parabolic reflector (Fig. 2-15) makes the antenna more directive than it would be with a flat reflector. Also, the concentration of signals from the curved surface onto the driven element provides more gain than would be possible with a flat reflector.

There are two basic types of parabolic reflectors: (1) the tuned reflector and (2) the solid, or "dish," reflector. The tuned reflector, consisting of wire reflector elements curved to form a parabolic surface, has the advantage of low wind resistance and less weight. However, the spacing between the reflectors and dipole is critical, as is the spacing between re-

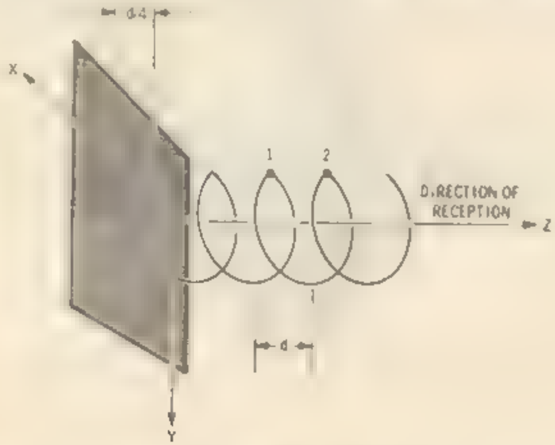


Fig. 2-16. The helical antenna.

flector elements. The solid reflector eliminates this problem. Solid reflectors are used most often at the high end of the uhf band (microwaves), where the radio waves act essentially like light waves. Most radar systems use some form of solid parabolic antenna, as do point-to-point microwave communication links. It is possible to concentrate radio waves into a narrow beam with a parabolic reflector, just as the headlight of an automobile can be beamed by its reflector.

The *helical* antenna (Fig. 2-16) produces a circularly polarized radiation, with extremely high gain and a very narrow beam width. The helical antenna is essentially a helix, or coil, with the turns spaced so that the radiation from each turn is in phase with other turns, thus adding to provide the high gain. The reflector, combined with circular radiation from the helix, produces the narrow bandwidth. However, the narrow bandwidth limits the helical antenna to special uses. A common use is in satellite tracking, where bandwidth is of little importance, but where high gain and directivity are essential.

3

UHF Propagation Problems

Propagation refers to the paths followed by radio waves from the transmitting antenna to the receiving antenna. There are four basic paths: the *direct* wave, the *ground* wave, the *reflected* wave, and the *sky* wave (which is a form of reflected wave). These four propagation paths exist at all frequencies. However, the direct wave and, to a lesser extent, the reflected wave are the most useful in uhf work.

DEFINITION OF RADIO-WAVE PATHS

The terms for radio-wave propagation are often intermixed and result in some confusion. For example, a direct wave is often called a direct *surface* wave since it follows the surface of the earth. This is sometimes confused with a ground wave, which also follows the earth's surface. However, the two are not the same. To understand uhf propagation problems, it is necessary to define the propagation paths.

Ground Wave

A ground wave (A in Fig. 3-1) follows the curvature of the earth from the transmitting antenna to the receiving antenna, staying close to the earth's surface at all points. A ground wave exists only where the transmitting antenna is a few wavelengths from the earth's surface. In uhf work, a few wavelengths can mean a few inches (a full wavelength at 900 MHz is only about one foot). Therefore, a uhf antenna raised a few feet into the air produces few or no ground waves. Also, to receive ground waves, it is necessary for the receiving antenna to be close to the ground. Of course, at lower frequencies a single wavelength will be several yards long, so there will be

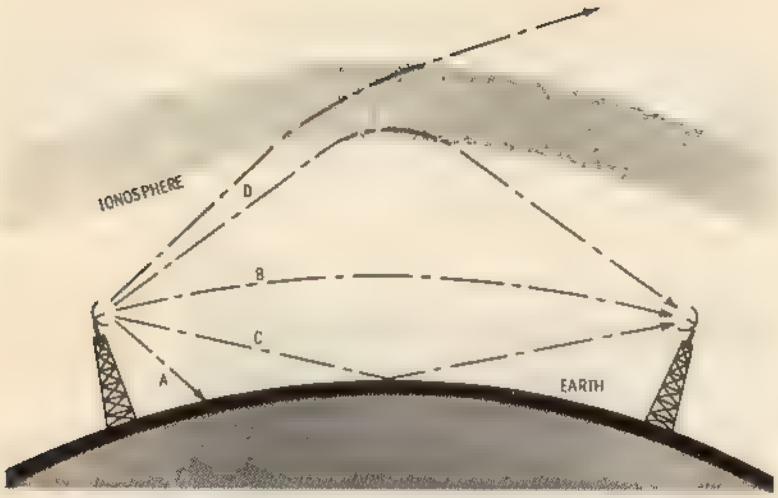
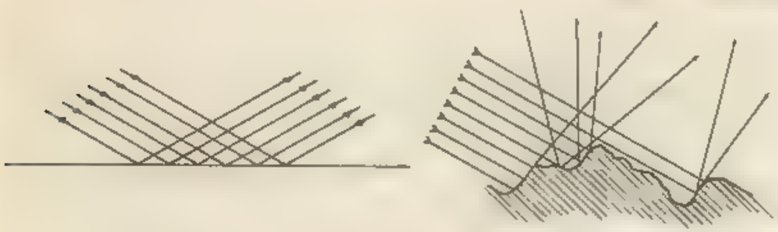


Fig. 3-1. Types of radio-wave propagation: (A) ground wave, (B) direct wave, (C) reflected wave, and (D) sky wave.

strong ground waves, even with high antennas. Ground waves are used most often in the very low frequency systems such as the broadcast band, and in the communications bands below 500 kHz.

Direct Wave

A direct wave (B in Fig. 3-1) theoretically travels from the transmitting antenna to the receiving antenna, as would a light beam. That is, it travels in direct line of sight. However, in actual practice, uhf radio waves do bend somewhat to follow the earth's curvature. As the frequency increases, radio waves tend to act more like light beams, and the curvature is less



(*A*) *Smooth surface.* (*B*) *Rough surface.*

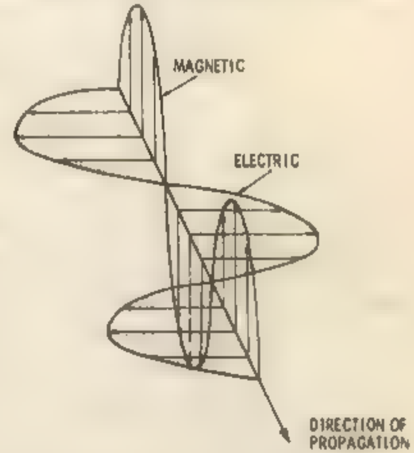
Fig. 3-2. Effect on reflected wave of smooth and rough surfaces.

apparent. In the microwave region, radio waves are almost identical to light waves. Over land, the direct wave is the only important method of propagation for both uhf communications and radar. Over water, the reflected wave is also an important factor.

Reflected Wave

A reflected wave (C in Fig. 3-1) travels from the transmitting antenna, strikes the earth's surface, and is reflected up to the receiving antenna. The reflected wave is added to the direct

Fig. 3-3. Radio-wave polarization.



wave, but not in all cases, and not always to the same extent. When waves strike a smooth surface (such as a large body of water), they are essentially parallel both before and after the reflection (Fig. 3-2A). When the same waves strike an irregular surface (such as most of the earth's surface), the waves are irregular in direction after they are reflected (Fig. 3-2B). Such irregular waves cannot add much to the transmission, since part of them will never arrive at the receiving antenna, or will arrive too late and too weak. Therefore, reflected signals are less useful over land than over water.

If a reflected wave arrives at the receiving antenna in phase with the direct wave, the two will add and increase the signal strength. However, if the reflected wave arrives out of phase with the direct wave, it will cancel the direct wave and attenuate the signal strength.

Sky Wave

The true sky wave (D in Fig. 3-1) travels from the transmitting antenna, strikes the ionosphere, and is reflected down to

the receiving antenna. Actually, the sky wave is *refracted*, or bent, by the ionosphere, but the net effect is that of reflection. Sky waves are used extensively in high-frequency work, and to some extent in very high-frequency work. However, as the fre-

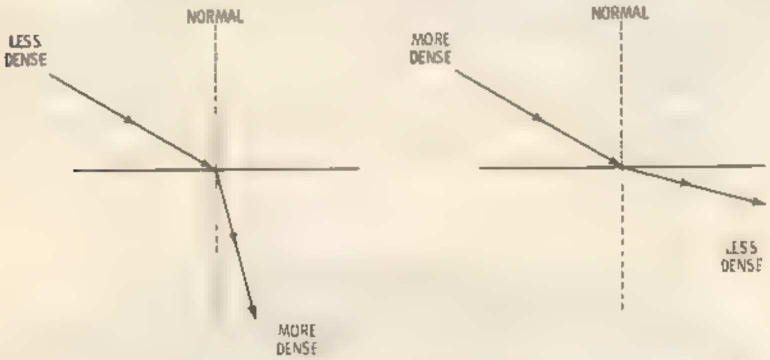


Fig. 3-4. Refraction effects.

quency increases, there is less reflection of the sky wave. Except for *scatter* propagation, which is not a true sky wave, the use of sky waves in uhf is negligible.

POLARIZATION OF RADIO WAVES

Radio waves are composed of both magnetic fields and electrostatic fields. These fields occur simultaneously and occupy the same space. However, they are at right angles (90°) to

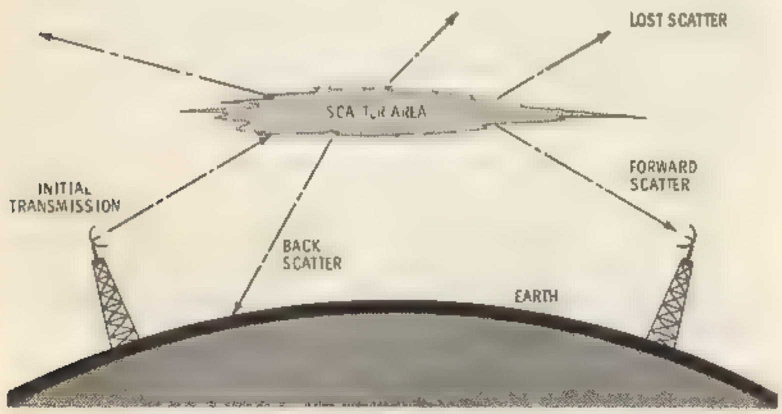


Fig. 3-5. Scatter propagation.

each other. Also, as the radio waves travel along a conductor such as an antenna, both the magnetic and the electrostatic fields are at right angles to the direction of travel. (See Fig. 3-3.) These fields alternate at the frequency of the radio wave. The radio waves are said to be horizontally polarized when the direction of the electrostatic field is horizontal, and vertically polarized when the direction of the electrostatic field is vertical. Normally, a horizontal transmitting antenna produces horizontally polarized waves and a vertical antenna produces vertically polarized waves.

PHASE RELATION OF DIRECT AND REFLECTED WAVES

As discussed previously, if direct and reflected waves arrive in phase at the receiving antenna, they will add. If they arrive exactly out of phase (180°), they will cancel. If the path of the reflected wave is varied, the amount of cancellation will be changed. For example, assume that the reflected wave arrives 180° out of phase with the direct wave and produces complete cancellation. If the reflected-wave path is increased by one-half wavelength, which could be done by raising either the transmitting or the receiving antenna, this would provide a 180° phase shift and bring both the direct and the reflected waves back in phase. The same condition could be accomplished by raising the antennas so that the path would be increased by any odd number of half-wavelengths.

NORMAL AND ABNORMAL PROPAGATION OF RADIO WAVES

Both direct and reflected radio waves are affected by refraction, even under normal conditions of propagation. Like light waves, radio waves are refracted, or bent, when they pass through environments of varying density. This effect is noticed when a light wave or ray passes through a glass prism. Because the glass is more dense than the surrounding air, the light wave is bent (refracted). When a light wave or radio wave passes from a less dense to a more dense area, the wave is bent toward a plane at right angles to the surfaces of the two areas. This plane is known as the *normal* (Fig. 3-4). When the waves pass from an area of lower to an area of higher density, such as when radio waves move to lower altitudes in their (apparent) direct path from the transmitting antenna to the receiving antenna, the waves are bent toward the normal,

and consequently, they appear to follow the curvature of the earth.

Because of this apparent curvature, there are two methods for establishing a line-of-sight path from a transmitting antenna to a receiving antenna. With the *optical* method, a clear view is required between the two points. With the *profile-diagram* method, the earth is considered to be "modified" so that its diameter is made larger (four-thirds) than the actual diameter, to account for the slight bending of the radio waves.

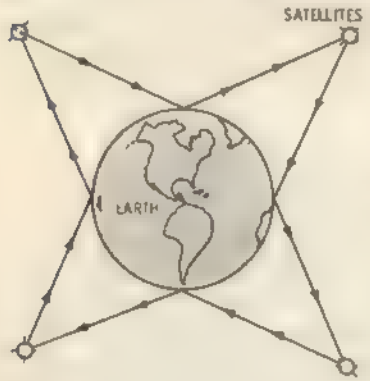


Fig. 3-6. Satellite communication arrangement.

The prime reason for the refraction of radio waves (and light waves) is that their velocity is changed as they pass through areas of different density. The "normal" speed of radio and light waves is 300,000,000 meters per second (186,000 miles per second) in a vacuum. This speed or velocity is just slightly slower through air. However, the radio-wave velocity is changed with changes in air temperature, atmospheric pressure, or water-vapor content. When one or more of these decrease (as usually occurs with increased altitude), the velocity increases. The relative velocity of wave travel (both radio and light waves) is known as the *index of refraction.*

Thus far, the normal propagation of radio waves has been discussed. Refraction will also occur under abnormal conditions. This is known as *anomalous*, or abnormal propagation. The most common is a *temperature inversion*, where the temperature (or water vapor) increases with altitude. This causes the radio waves to be refracted in one direction, at the point where the temperature inversion occurs, and then to be refracted back in the normal direction at the point where the temperature decreases with altitude in the normal manner. This condition creates a "duct" through which the radio waves travel. There are surface ducts, where the temperature inversion occurs close to the earth's surface, and sky ducts, where the inversion occurs at high altitudes. It is possible for uhf radio waves to travel much greater distances through these ducts than through the normal line-of-sight paths. However, the duct condition is an abnormal one and cannot be used for reliable communication.

ABSORPTION OF RADIO WAVES

Certain gases, such as oxygen and water vapor, have a molecular structure that will oscillate at high frequencies. In effect, these gases form resonant circuits, and they actually absorb energy from radio waves passing through them. This effect becomes slightly noticeable at the high end of the uhf band, in the microwave region. This is one reason why uhf sky waves are attenuated, rather than being reflected as useful waves.

SCATTERING OF RADIO WAVES

In addition to being absorbed, radio waves can be scattered by small particles of moisture, ice, dust, snow, etc., which may be in the atmosphere between the transmitting and receiving antennas. This scattering is a result of the waves being reflected by these particles. The reflections are in an irregular pattern. Usually they are at right angles to the desired path, and possibly in direct opposition to it. (See Fig. 3-5.) The higher the frequency, the more the scattering effect is noticed.

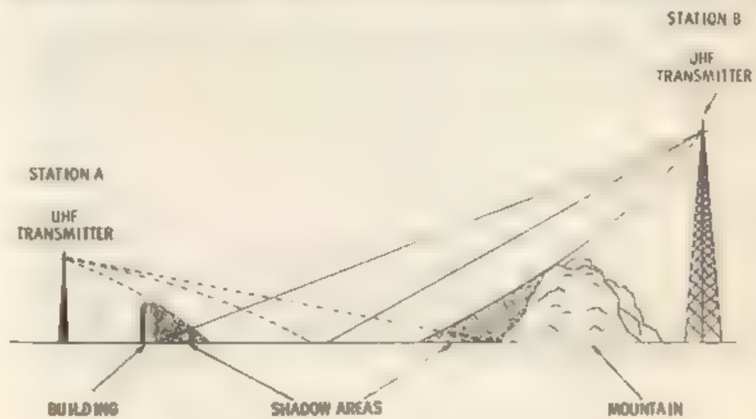


Fig. 3-7. Line-of-sight transmission effects.

Although most of the signal is lost through scattering, a small portion can be used. An example of this is the Forward Propagation Tropospheric Scatter (FPTS) system used in the Arctic regions to provide communications where atmospheric conditions often black out normal radio communications.

The FPTS system uses the scatter effect from the troposphere. Although most of the signal is lost, a small portion is directed forward beyond the horizon. The operating frequencies are in the uhf band, from 500 to 750 MHz. To eliminate fading, two receivers are used in each direction. A switching (dual diversity) system is incorporated that permits the receiver with the stronger signal to be used at any given time. The system uses f-m multiplex techniques, to provide for approximately 40 channels of operation.

Although such systems can use scattering from any section of the upper atmosphere which differs from its surroundings, the ionized air from meteor trails is the most effective. Each day, the earth's upper atmosphere is filled with meteor trails by the thousands. Although the meteors are destroyed, they leave trails of ionized air which act as reflectors.

ARTIFICIAL REFLECTION

Radio waves can, of course, be reflected artificially. This is the basis for the communications satellites. If three or four such satellites are placed in orbit around the earth, it is possible to cover the entire earth's surface, as shown in Fig. 3-6.

THE EFFECTS OF LINE-OF-SIGHT PROPAGATION

There are two line-of-sight effects that have a detrimental effect on uhf propagation. One of these is the *shadow* effect; the other is ghosts.

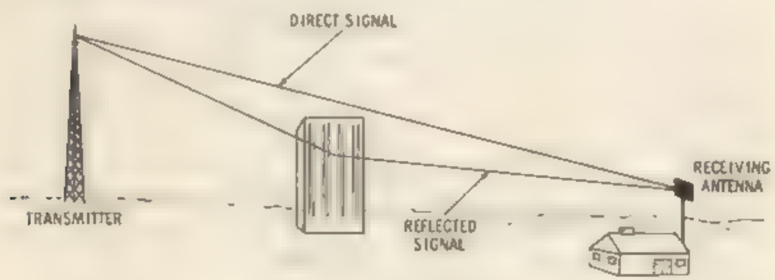


Fig. 3-8. How ghost signals are created.

Because of the line-of-sight effect, anything between the transmitting and receiving antenna will attenuate, if not completely block, the signal to the receiving antenna. This effect is known as a uhf shadow. As shown in Fig. 3-7, receivers in the shadow areas are blocked from receiving signals from one of the two transmitters. In metropolitan areas, tall buildings can create very effective uhf shadows. Mountains, and even low rolling hills, can produce the same condition in rural areas.

Very little can be done from the receiving end. The only practical solution is to raise the receiving antenna as high as possible, out of the shadow, so there will be a line-of-sight path between the transmitting and receiving antennas. In shadow areas where the signal is attenuated but not completely blocked, a high-gain antenna may produce a strong enough signal for good reception. However, obstructions (tall buildings or mountains) will usually block the signal completely rather than attenuate its strength.

A shadow area should not be confused with a fringe area. A true shadow area is one where the signal is blocked by an obstruction, even though the receiver may be well within range of the transmitter's broadcast pattern. A fringe area is one where the signal is attenuated by distance from the transmitter. The most practical solution to both the shadow and fringe-area problems in uhf television is the repeater or translator station.

Ghosts are a major problem in uhf. Solid objects will easily reflect uhf radio waves. As shown in Fig. 3-8, the reflected signal will be delayed by a few microseconds, resulting in a double image on a tv screen, when a receiver picks up both a direct and a reflected signal. The ghost effect is not too important with uhf communications, except for possible cancellation of the direct signal, but is quite a problem for uhf television. About the only solution to the problem is to use a highly directional antenna. Fortunately, most uhf antennas are more directional than vhf or lower-frequency antennas. They can be oriented on the station's antenna, attenuating signals from all other directions. However, this high directivity creates a problem in itself. If a uhf antenna is not "bang on target," considerable signal strength can be lost. The problem becomes more serious when more than one uhf channel is available. Unless the transmitting antennas of all the stations are close together, several receiving antennas or a rotating antenna may be needed.

4

UHF Transmission Lines

The transmission lines used in uhf are basically the same as those used at lower frequencies. The basic function of any transmission line is to transfer energy from a transmitter, or other source of r-f energy, to an antenna, or other load. The same line can also be used to connect an antenna (now acting as a source) to a receiver (acting as the load). However, in uhf work, a transmission line can be used as a resonant circuit (with capacitance and inductance), and as a filter, insulator, or transformer.

Chapter 5 covers the use of transmission lines as resonant uhf circuits. To understand such uses, it is essential that the student of uhf first understand basic transmission-line characteristics. They are discussed in this chapter.

BASIC TRANSMISSION-LINE TERMS AND DEFINITIONS

The following sections describe the principal terms and definitions applicable to transmission lines.

Transmission Line (Lead-In)

A transmission line (lead-in) is any device that will conduct electrical energy from a source to a load. The term "lead-in" is usually applied to a conductor between the antenna and a receiver, while "transmission line" usually means the line between a transmitter and antenna. Since the same types of wire are used in both applications, the terms are actually interchangeable. The generator, or input end of the transmission line, is connected to a source of energy; this end is known as the source, or sending, end. The opposite end of the line is con-

nected to a load, and is usually known as the receiving, or sink, end. In most uhf applications, two wires are required for a transmission line, since antennas are usually dipoles or grounded monopoles. Two basic types of lead-in or transmission line are *parallel-wire* lines and *coaxial* lines. To break it down further, parallel-wire lines can be of the *open-wire* type, where there is no material between the conductors except widely separated spacers. More likely for television reception, it will be *flat ribbon* (twin-lead) or possibly *tubular* line. Coaxial lines are those where a center conductor is completely surrounded by the outer conductor, which also serves as a shield.

Transmission-Line Impedance

As discussed in Chapter 5, transmission lines have all the characteristics of a resonant circuit (resistance, capacitive reactance, and inductive reactance). Therefore, in the presence of an a-c or r-f voltage, transmission lines have a character-

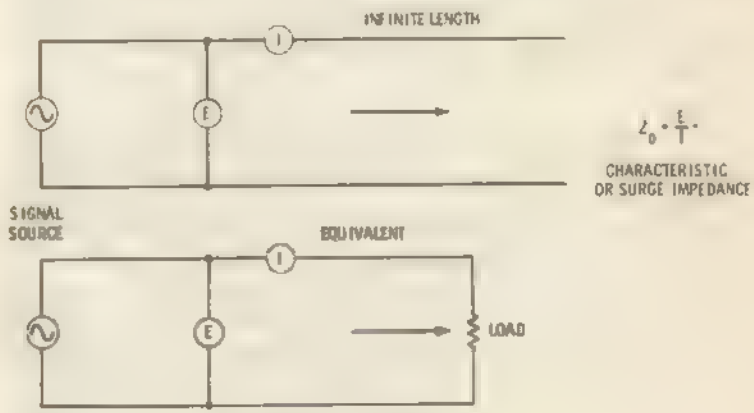


Fig. 4-1. Characteristic impedance of a transmisison line.

istic impedance. This is sometimes known as a surge impedance. It remains the same for any length of line. In a transmission line of infinite length, energy applied to the generator end theoretically never reaches the load end, since it would eventually be dissipated in the form of heat. However, there would still be a measurable voltage and current at the generator end. The *apparent* size of the load being fed by the signal source, which is the load presented by the line, can be determined by

measuring the voltage and current at the generator end (Fig. 4-1). When the voltage is divided by the current, the result is the characteristic, or surge, impedance (Z_o) of the line. If a line is terminated by a resistance, or load, that has the same value as the line impedance, this load will have the same voltage and current relationship as the line.

Calculating Transmission-Line Impedance

The impedance of a transmission line could be measured electrically if an infinitely long section of line were available and if the voltage and current were measured at the generator end. However, this could only be accomplished under laboratory conditions, where a line several hundred (or thousand)

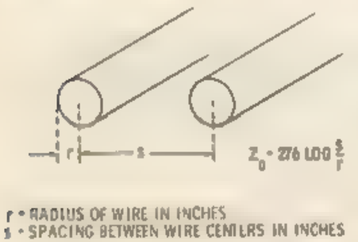


Fig. 4-2. Calculating the impedance of an open, two-wire line.

feet long was fed a very low-power signal. Even then, some of the energy might reach the end of the line. For practical purposes, the impedance of a transmission line can be calculated by physical measurement of the conductor diameter or radius, as well as the spacing between conductors.

For an open, two-wire transmission line using an air dielectric (no solid dielectric separating the two wires), the impedance can be calculated by the following equation (see Fig. 4-2):

$$Z_o = 276 \log \frac{s}{r}$$

where,

Z is the impedance of the transmission line,
s is the spacing between the wire centers in inches,
r is the radius of the wire in inches.

For coaxial transmission line, or any concentric transmission line, the impedance can be calculated by the following equation (see Fig. 4-3):

$$Z_o = 138 \log \frac{D}{d}$$

where,

Z is the impedance of the transmission line,
D is the inside diameter of the outside conductor in inches,
d is the outside diameter of the inside conductor in inches.

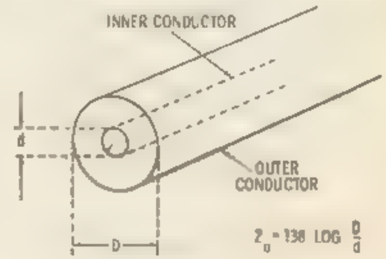


Fig. 4-3. Calculating the impedance of a coaxial or concentric line.

Artificial Transmission Lines

Since a transmission line consists essentially of a two-wire conductor with capacitance, inductance, and resistance, it is possible to create an artificial transmission line by combining these circuit elements as shown in Fig. 4-4. The resistance element is added by the effect of leakage across the capacitors (for shunt resistance) and the natural resistance of the inductor coils (for series resistance). Such artificial lines are used where a line of a given electrical length is required, but where the corresponding physical length would be too large to fit the available space.

One of the prime uses for an artificial line is as a *delay* line. Many times, particularly in pulse circuitry, it is desirable to delay a pulse or other signal by a few microseconds. The delay must be exact in time, and there must be no other changes to the signal or pulse except the delay. Because of the impedance, a transmission line will delay signals in comparison to their passage through free space or through a conductor. The longer the line, the greater the delay. However, a transmission line

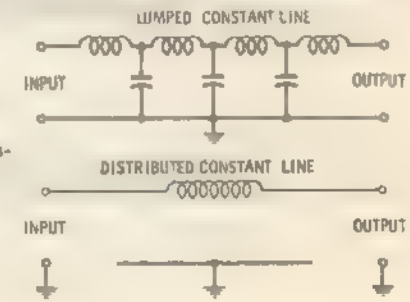


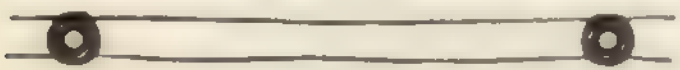
Fig. 4-4. Typical artificial transmission lines.

would have to be many, many feet long to cause a delay of a few microseconds. Since this is not practical, a compact artificial line will provide the necesary delay, but will take up only a fraction of the space. Delay lines are often used in radar circuits and are sometimes used in computer circuits for storage of information.

There are two basic types of delay lines: (1) the *lumped-constant* line and (2) the *distributed-constant* line. As the names imply, the distributed-constant line is made so that the capacitance and inductance values are spread or distributed across the entire line, while in the lumped-constant line the same values are lumped by a series of inductors and capacitors connected together.

Types of Transmission Lines

There are four basic types of transmission lines used in uhf work: open-wire line, coaxial line, flat ribbon line, and tubular line. Practically all uhf transmitter applications use coaxial line. The same is true of most uhf communication receiver applications. However, the ribbon or tubular line and (in a few cases) the open-wire line are used in uhf television applications. Each type of line has its own particular advantages and disadvantages.



(A) Open wire.

(B) Coaxial cable.

(C) Twin-lead.

(D) Tubular.

Fig. 4-5. Types of transmission line.

The open-wire line (Fig. 4-5A) has the least loss because air is the dielectric. The two conductors are separated at intervals by polyethylene spacers. There is little chance for dirt or moisture to build up across the open leads, so an open-wire line is a good choice for very long runs, where losses must be kept to a minimum. However, the open-wire line is difficult to install, and it deteriorates from exposure to elements faster than other types of line. It is available with a nominal impedance of 300 ohms (½-inch spacing between conductors) or 450 ohms (1-inch spacing).

Because of its shielding, coaxial line (Fig. 4-5B) is the best bet where there are radiation problems, or where exposure to the elements is a problem. Most coaxial cable consists of an inner conductor embedded in polyethylene, which serves as the dielectric. This is enclosed in a copper braided shield and a vinyl jacket for weather and abrasion protection. In some high-power uhf transmitter applications, the coaxial dielectric is made up of beads spaced along the line. These reduce dielectric losses by reducing the amount of dielectric material. In other applications, the coaxial line is pressurized with a low-pressure gas. The gas keeps moisture from entering the line, and thereby helps to keep the line characteristics constant. When moisture or moist air is present across the two conductors, there will be a power loss and possibly a change in characteristic impedance. Properly designed coaxial line is virtually unaffected by moisture and dirt outside the line. Also, nearby conductors will not absorb energy from the line; nor will interference signals enter the line. There is little or no radiation from a coaxial line. Coaxial line is fairly simple to install, but it does require a hole at the feedthrough point. Coaxial-line impedance varies from about 50 to 75 ohms, which matches most communications-type antennas. However, it does not match the normal uhf television antenna impedance of 300 ohms, so a matching transformer is required. A matching transformer is also needed when you are connecting to a 300-ohm input on the tv set.

As in the case of vhf television, the flat ribbon line or twin-lead (Fig. 4-5C) is the most popular lead-in for uhf television. One reason is that it can usually be routed into the house without drilling holes, by slipping it under a window. Twin-lead is readily available since it is also used for vhf television. Its impedance is normally 300 ohms, so it will match most uhf television antennas. Also available is a narrower, 72-ohm twin-

lead. In addition to the conventional flat ribbon, twin-lead is available in a punched or slotted ribbon, where much of the insulating material between the leads has been removed. This reduces losses, as long as the line is kept dry and clean. Dirt or moisture can accumulate in the slots or holes, however, making the losses almost as bad as with conventional ribbon line. In another version of the ribbon line, a polyethylene covering or sheath is placed over the line. This protects the line from the elements, so it shows considerably lower losses than other twin-lead when the lines are wet.

One of the best all-weather lead-ins for uhf television is the tubular line (Fig. 4-5D). It was designed to keep losses down when the lead-in is wet, or covered with dirt and snow. As shown in Fig. 4-6, the energy fields between the two conductors

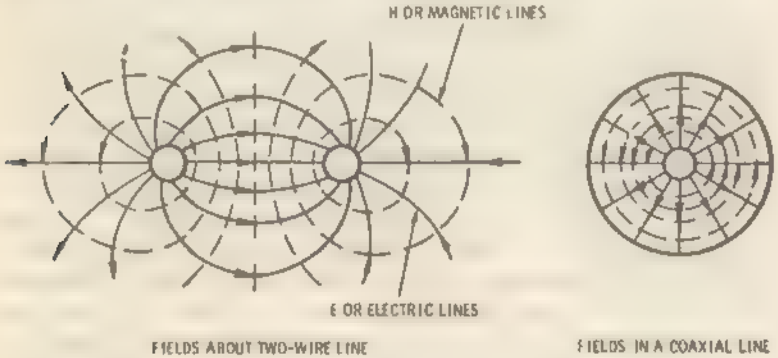


Fig. 4-6. Electric and magnetic fields in transmission lines.

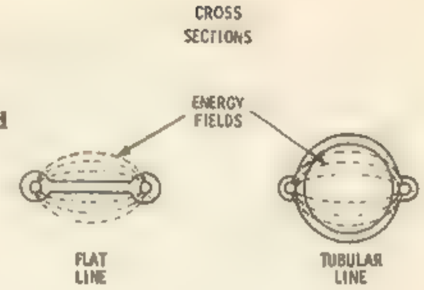
of a transmission line are essentially circular. The magnetic fields surround the two conductors, while the electrical fields appear as lines between them. With conventional flat line (Fig. 4-7), the energy fields are outside the insulation. When moisture is present, it acts as a high-resistance shunt between the conductors, causing additional losses. On tubular line, the moisture remains outside the field of energy.

Transmission-Line Losses

All transmission lines have some losses. That is, part of the energy or signal will be lost in the transfer from the source to the load. There are four basic reasons for such losses:

1. Since a transmission line is carrying an r-f signal, a portion of that signal is radiated out from the line (Fig.4-8). This is known as radiation loss. It is present on lower-

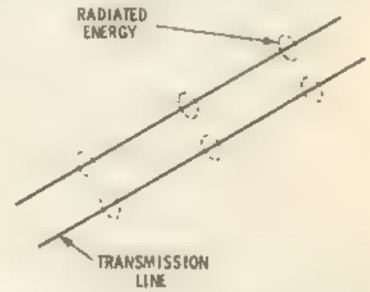
Fig. 4-7. Cross sections of flat and tubular line.



frequency transmission lines to a limited extent, but it only becomes a problem at the ultrahigh frequencies. Because the outer conductor of a coaxial line also serves as a shield, coaxial lines have a minimum of radiation loss.

2. When a transmission line is routed near another conductor, part of the energy radiated out is transferred to the

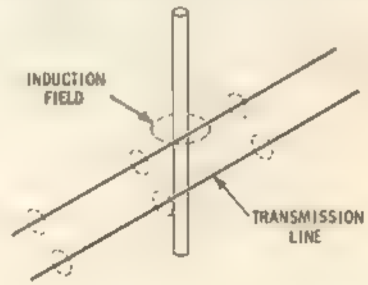
Fig. 4-8. Radiation loss in transmission lines.



conductor by induction. This is known as induction loss (Fig. 4-9). Since induction loss is a result of radiation, it will be at a minimum when coaxial lines are used.

3. The insulating material between the two transmission wires forms a dielectric which acts as a high-resistance shunt. A portion of the energy or signal is lost across this

Fig. 4-9. Induction loss in transmission lines.



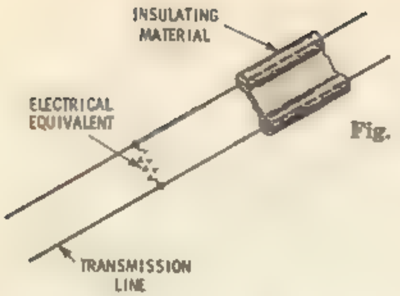


Fig. 4-10. Dielectric loss in transmission lines.

shunt (Fig. 4-10). This is known as dielectric loss. Fortunately, dielectric losses are not too great under normal circumstances. Although dry air is the dielectric which offers the most resistance (and the least losses), moist air is a very poor dielectric. Likewise, flat ribbon lines normally have a low loss, but when they are wet or dirty the effect is to change the dielectric to one with higher losses.

4. All conductors have some resistance which will cause a loss in the currents flowing through them (Fig. 4-11). This is known as resistance loss. For uhf transmission line, the d-c resistance loss is very small (usually less than 1 ohm per 100 feet). However, because of skin effect, r-f resistance losses can be quite large.

Skin effect results from the fact that r-f currents tend to travel on the surface of the conductors rather than through the entire conductor. Since resistance depends on the cross-sectional area through which the current passes (the smaller the area, the higher the resistance), the r-f resistance of a given conductor can be considerably higher than the d-c resistance. As the frequency of the r-f currents increases, the skin effect becomes more pronounced. Actually, the resistance

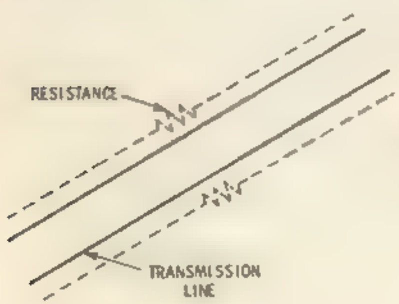


Fig. 4-11. Resistance loss in transmission lines.

of a hollow tube and a solid conductor, both of the same diameter, is about the same at high frequencies. Hollow tubes are used for many uhf circuit applications, but they are not practical for lead-ins. Because of skin effect, many uhf circuits are silver-plated. R-f currents traveling on the outer surface meet less resistance since silver is a much better conductor than copper. Skin effect is measured in terms of skin depth or penetration depth, which is the thickness of the material that is actually carrying r-f currents. As the frequency increases, the depth decreases and the resistance increases. R-f resistance varies directly with the square root of the frequency. Thus, the r-f resistance will double when the lead-in used for vhf at 200 MHz is used for uhf at 800 MHz.

Transmission-Line Attenuation

The combination of the four types of line losses results in a net attenuation of the signal. This is usually expressed in db per 100 feet, or in percentage of efficiency. Table 4-1 shows the

Table 4-1. Line Attenuation versus Efficiency

Efficiency (percent)	Attenuation	Efficiency (percent)	Attenuation
93	0.1	60	2.0
90	0.2	47	3.0
89	0.3	35	4.0
87	0.4	30	5.0
85	0.5	22	6.0
83	0.6	18	7.0
80	0.7	15	8.0
78	0.8	12	9.0
76	0.9	9	10.0
74	1.0	1	20.0

relationship between attenuation in decibels and efficiency in percent. Obviously, attenuation increases with length. To be of real value, however, the attenuation factor of a lead-in should be related to the entire frequency range used, as well as the surrounding conditions.

Transmission-Line Velocity

Radio waves traveling through a transmission line are slowed down by the line. That is the principle of a delay line. The ratio of radio-wave velocity through a transmission line to the velocity through open air is the *velocity constant*. This

is usually expressed as a percentage of the free-space velocity. As shown in Table 4-2, the velocity constant varies with the type of transmission line. Since velocity is affected by transmission lines, wavelength is also affected. For example, if the

Table 4-2. Transmission Line Characteristics

Type of Line	Velocity Constant
Open Wire Line	.975
RG-58/U	.66
RG-59/U	.66
Twin-Lead, 300-ohm	.85
Twin-lead, 150-ohm	.77
Twin-lead, 75-ohm	.68

velocity constant is .70 (70%), the wavelength of any given frequency on such a transmission line is 70 percent of the free-space wavelength. This is why resonant transmission lines and antennas are usually cut shorter than the free-space wavelength.

MATCHING TRANSMISSION LINES

When a transmission line is used for its primary purpose of transferring energy from a source to a load, rather than as a resonant circuit, the line should be matched. That is, the impedance of the load should be equal to the characteristic impedance of the line. If the load is pure resistance, such as a carbon resistor, then its resistance should equal the line impedance. When a transmission line is properly matched or terminated, there will be maximum transfer of energy from the source to the load. This is an ideal condition and is rarely achieved in actual practice. However, the closer the match between a transmission line and its load, the greater will be the transfer of energy, and losses will be at a minimum. Besides the maximum transfer of energy, a perfectly matched line will also show certain other characteristics. These are:

1. At any point along the transmission line, the voltage and current will be in phase.
2. If the voltage is divided by the current at any point along the line, the resultant impedance value will be equal to the surge, or characteristic, impedance of the line.
3. There will be a minimum amount of radiation from the transmission line itself.

4. The input impedance, or the impedance seen by the generator, is equal to the characteristic impedance of the line.
5. There will be a decrease in power from the generator end of the transmission line to the load end. However, this decrease will be the result of line attenuation and not mismatch.

MISMATCHING TRANSMISSION LINES

There are two ways in which a transmission line can be mismatched. If the load is pure resistance and it does not equal or even closely approximate the transmission-line impedance, there will be some mismatch. If the load is a combination of resistance and reactance (either capacitive or inductive), there will be a mismatch. For example, assume that the load is an antenna. The impedance of an antenna, or any other device operating with a-c or r-f energy, depends on resistance, capacitive reactance, and inductive reactance. At the resonant frequency of the antenna, the capacitive and inductive reactances are equal and so they cancel each other, leaving nothing but resistance. If this resistance is equal to the line impedance, there will be a match between line and antenna. At any frequency other than resonance, the capacitive and inductive reactances will not be equal. When one is subtracted from the other, some reactance will remain, either capacitive or inductive. It will be added to the pure resistance and result in a mismatch between the line and antenna.

RESULTS OF MISMATCHED TRANSMISSION LINES

The major result of a mismatched transmission line is the reflection of energy from the load end back toward the generator end. This reflected energy causes a loss of energy since it

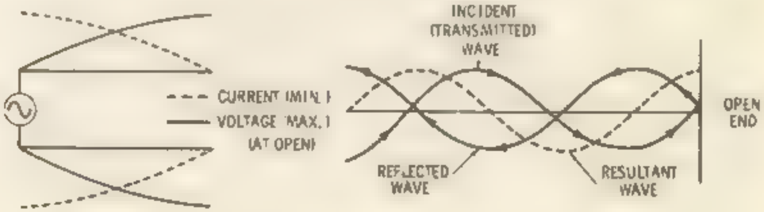


Fig. 4-12. Open-ended line with reflections.

partially cancels the transmitted energy. In effect, the load acts like another generator working in opposition to the original generator.

This effect can be better understood by reference to Figs. 4-12 and 4-13. These illustrations show how voltage waves passing down a transmission line are reflected when the line is not terminated in its own impedance. Fig. 4-12 shows a line which is open at the load end. This is equivalent to a line terminated in an impedance much higher than that of the line. Fig. 4-13 shows a line which is shorted at the load end. This is equivalent to a line terminated in an impedance much lower than that of the line.

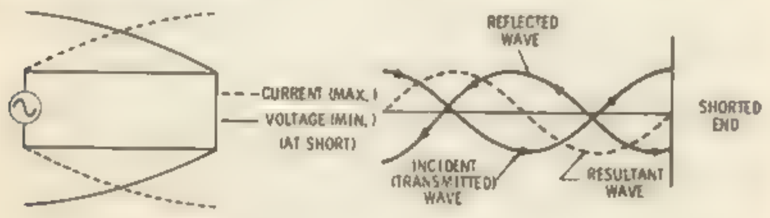


Fig. 4-13. Shorted line with reflections.

When energy reaches the end of the open-ended line (Fig. 4-12), it encounters an infinite impedance. It cannot go farther and it cannot remain because there is nothing to absorb it. Therefore, it must be reflected back along the line. If the line is open, the voltage will be maximum and current will be minimum, just as is the case when a voltage is placed across a very large resistance. This means that the voltage of the reflected wave of energy will be maximum at the load end, no matter what the transmitted (or incident) voltage may be at the load. The transmitted and reflected waves are combined and produce a resultant wave, which is also maximum (voltage) at the load end. The resultant waves are also called standing waves. The greater the standing waves, the greater the mismatch. Refer to "Antenna Vswr," Chapter 2.

When energy reaches the end of the shorted line (Fig. 4-13) it encounters zero impedance. Again, it can go no farther, and it cannot remain since there is nothing to absorb it. Therefore, it will be reflected back along the line, but in exactly the opposite manner to that of an open-ended line. If the line is shorted, the voltage will be minimum and the current will be maximum, just as is the case when a voltage is placed across a short or a very low resistance. This means that the voltage of the reflected wave of energy will be minimum at the load end, no

matter what the transmitted voltage may be at the load. The transmitted and reflected waves are combined and produce a resultant, or standing, wave.

SENDING OR INPUT IMPEDANCE

As stated, the sending or input impedance (the impedance that the generator "sees") in a perfectly matched line is equal to the characteristic impedance of the line. When there is a mismatch, the input impedance is measured by the resultant (or standing) voltage and current waves appearing at the gen-

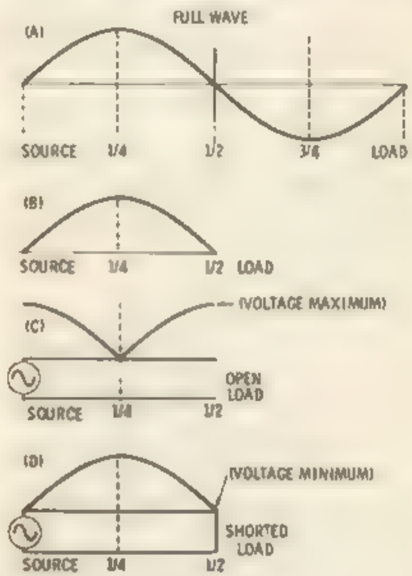


Fig. 4-14. Basic characteristics of half-wave line.

erator end of the line. The input impedance is determined by dividing the voltage by the current.

The relationship between the voltage and current at any point along the line is determined by three factors: (1) the frequency, (2) the wavelength of the line, and (3) the reactance of the termination. The effect of each factor can best be understood by reference to Figs. 4-14 and 4-15.

As shown in Fig. 4-14A, if the transmission line is a full wave long at the operating frequency, the transmitting voltage will start at zero, rise to maximum at the quarter-wave point, drop to zero at the half-wave point, swing to the opposite maxi-

mum at the three-quarter wave point, and return to zero at the full wavelength. Therefore, whatever condition occurs at the load end will be duplicated at the generator end. As shown in Fig. 4-14B, if the transmission line is a half-wave long, the transmitting voltage will start at zero, rise to maximum at

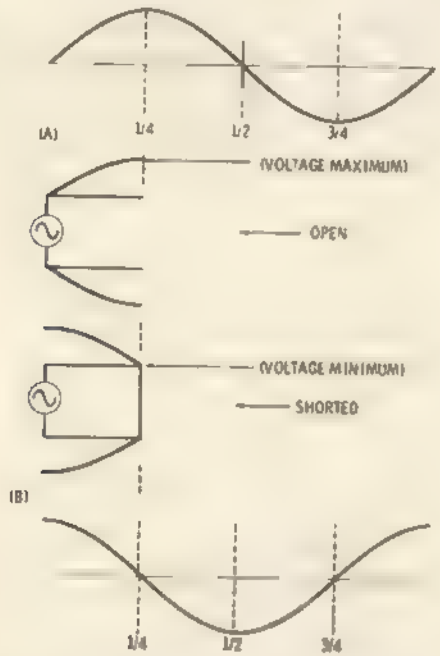


Fig. 4-15. Basic characteristics of quarter-wave line.

the quarter-wave point, and return to zero at the half-wave point. Therefore, whatever condition occurs at the load end will be duplicated at the generator end, except that the phase will be inverted.

Now assume that this same half-wave line is open-ended (Fig. 4-14C). As previously discussed, an open-ended line will produce reflected waves, and they will have a voltage maximum (current minimum) at the open end. Since a half-wave input is a duplicate of the load (except for phase), the input voltage will also be maximum while the input current is minimum. Also, since the input impedance is the result of voltage divided by current, the impedance will be high. Therefore, an open-ended, half-wave transmission line has high impedance and, as will be discussed in Chapter 5, acts like a parallel-resonant circuit.

Assume that the same half-wave line is shorted at the load end (Fig. 4-14D). As discussed, a shorted line will produce reflected waves, and they will have a voltage minimum (current maximum) at the shorted or load end. Again, a half-wave input is the duplicate of the load. Consequently, the input voltage will also be minimum while the input current is maximum, and the input impedance will be low. In effect, a shorted half-wave transmission line acts like a series-resonant circuit.

Now assume that the line is cut to a quarter-wave, or that the operating frequency is changed (cut in half) so that the line appears to be a quarter-wave long. The transmitting voltage will start at zero and rise to maximum at the quarter-wave or load end. Therefore, whatever condition occurs at the load end will be reversed at the generator end.

If this quarter-wave line is open-ended (Fig. 4-15A), the reflected waves will have a voltage maximum (current minimum) at the open end. However, since a quarter-wave input is the opposite of the load, the input voltage will be minimum while the current is maximum, resulting in a low impedance. Therefore, an open-ended, quarter-wave line acts like a series-resonant circuit.

If the quarter-wave line is shorted at the load end (Fig. 4-15B), the reflected wave will have a voltage minimum (current maximum) at the shorted end, but will have a voltage maximum (current minimum) at the input end. Consequently, the input impedance will be high, and a shorted quarter-wave line will act as a parallel-resonant circuit.

It should be noted that in actual practice, true transmission lines (those used to connect antennas to transmitters and receivers) are rarely cut for any particular electrical length. Instead, they are cut to meet physical requirements. However, where transmission lines are used as uhf resonant circuits, their physical and electrical lengths become of particular importance. This is discussed further in Chapter 5.

5

Resonant Circuits in UHF

The one major difference between uhf circuitry and circuitry of lower frequencies is that uhf uses parallel-line or coaxial tank circuits instead of the usual coil-capacitor tank circuit found in the lower frequencies. The reason is that the ultrahigh frequencies require an inductance-capacitance combination which is difficult, if not impossible, to achieve with conventional coils and capacitors. Even a one-turn coil, in combination with the smallest variable capacitor made, would produce a resonance below the uhf range. On the other hand, it is not difficult to cut a parallel line or a coaxial tank to a quarter wavelength in the uhf range. These parallel lines or coaxial tanks are essentially transmission lines. Therefore, it is essential that you make a thorough study of Chapter 4 on transmission lines before attempting to study the material in this chapter.

USING LINES AS RESONANT TANK CIRCUITS

Transmission lines can be used as resonant circuits because they have inductance, capacitance, and resistance. As shown in Fig. 5-1, two parallel conductors (e.g., a transmission line) have capacitance and inductance. The operation of parallel lines as resonant circuits can best be understood when each factor is broken down and studied separately.

A single piece of wire or conductor has inductance. Since inductive reactance increases with frequency, it will be high when uhf currents are involved. If a second piece of wire is placed parallel to the first, the second wire also will have inductance, and there will be mutual inductance between the lines. Being conductors, the lines have some resistance. There will

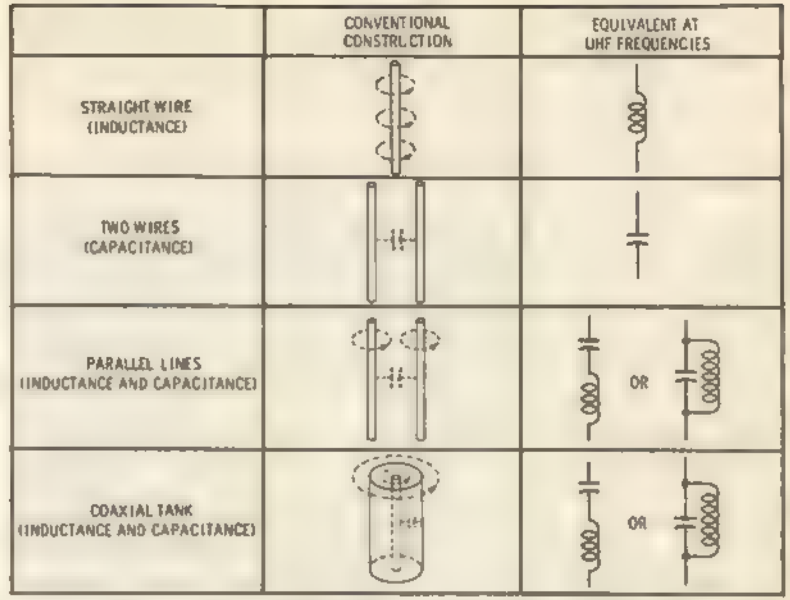


Fig. 5-1. Wire equivalents at ultrahigh frequencies.

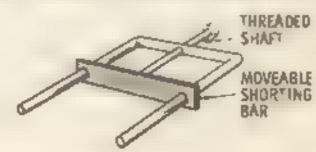
also be capacitance between them. This combination of inductance, capacitance, and resistance produces a resonant circuit, just as conventional coils and capacitors do.

The same effect is produced by a coaxial tank, which is essentially one parallel line within a larger parallel line. Both lines still have inductance, and there is capacitance between them. Parallel lines and coaxial lines differ in construction and methods of tuning, but they are the same in operation.

TUNING LINES TO A RESONANT FREQUENCY

The resonant frequency of any tank circuit is determined by the amount of inductance and capacitance involved. In a conventional coil-capacitor tank circuit, the inductance (and consequently, the resonant frequency) can be increased or decreased by adding or removing coil turns, which lengthens or

Fig. 5-2. Parallel-line tuning with shorting bar.



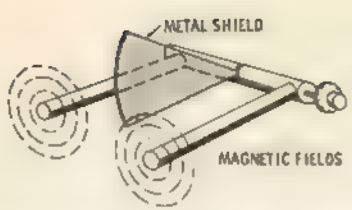


Fig. 5-3. Parallel-line tuning with magnetic shield.

shortens the coil. In parallel-line or coaxial tanks, the inductance can be varied by lengthening or shortening the line. In a coil-capacitor tank circuit, the frequency can also be varied by changing the capacitor value. In parallel-line or coaxial tanks, the frequency can be changed by varying the capacitance between the lines.

In practical applications, parallel lines are lengthened or shortened by placing a shorting bar across the lines (Fig. 5-2). The shorting bar is usually driven by a screw arrangement coupled to the tuning shaft. Instead of changing the length, some parallel lines are tuned by means of a movable shield between them (Fig. 5-3). This shield serves to vary the magnetic coupling between the lines, thus varying the mutual inductance. Because there may be some backlash in the screw drive for shorting bars, parallel lines are often provided with trimmer capacitors. Coaxial lines are tuned by varying the capacitance between the inner and outer conductors, since it is not practical in most cases to vary their length (Fig. 5-4).

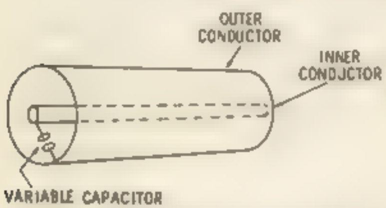


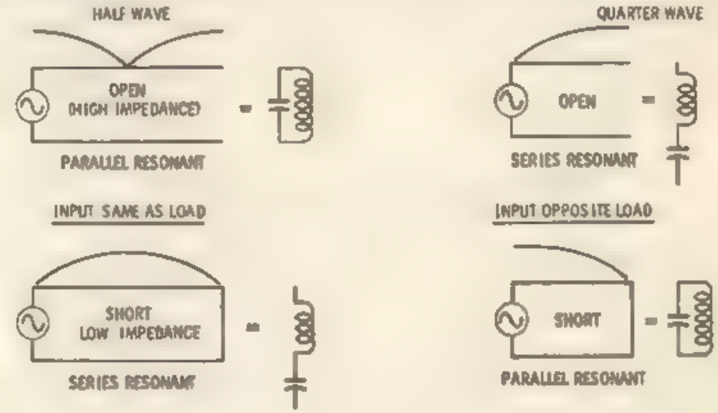
Fig. 5-4. Coaxial-line tuning with variable capacitor.

One of the major problems in tuning parallel lines is that of *resonant suckout.* As the shorting bar is moved toward the center of the lines, the unused portion becomes the same approximate length as the used or resonant tank portion. Therefore, the unused portion is resonant at the same frequency, and will absorb some of the energy from the used portion. The same condition will occur when the shorting bar is moved to one-third of the total length. The resonant or used portion is two-thirds of the total length. Assuming that this is a quarter wave at the operating frequency, the unused one-third is one-eighth wave length, and will also absorb some energy. Because of the resonant-suckout problem, the coaxial tank circuit with

some form of capacitive tuning is in greater use than the parallel line with shorting bars.

HALF- AND QUARTER-WAVE RESONANT LINES

Transmission lines of various wavelengths could be used as resonant circuits. However, for practical purposes, the quarter-wave and half-wave lines are used to the greatest extent. Going further, the shorted quarter-wave line (parallel resonant) is used most often. Therefore, the student of uhf circuitry should carefully memorize the characteristics of both half- and quarter-wave lines. Not only are these used as resonant tank circuits, but also as filters, insulators, balance-to-unbalance converters, transformers, and frequency-measuring devices.



(*A*) *Half-wave line.* (*B*) *Quarter-wave line.*

Fig. 5-5. Characteristics of half- and quarter-wave resonant lines.

Fig. 5-5 shows the important characteristics of half- and quarter-wave lines when used as resonant circuits. The following summarizes these characteristics:

Half Wave

1. The input to a half-wave line is identical to the load, except that the phase is shifted 180 degrees.
2. If the load or end is shorted, the short is seen at the input.
3. A short produces maximum current and minimum voltage at the resonant frequency. Therefore, a shorted half-wave line acts like a low impedance or series-resonant circuit. Signals at the resonant frequency are passed.
4. If the load or end is open, the open is seen at the input.

5. An open produces minimum current and maximum voltage at the resonant frequency. Therefore, an open half-wave line acts like a high impedance or parallel-resonant circuit. Signals at the resonant frequency are rejected.

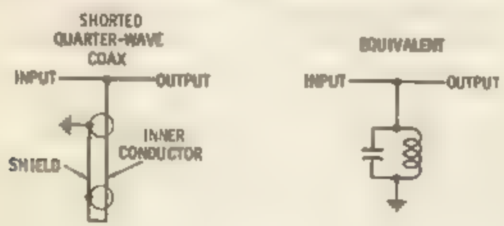
Quarter Wave

1. The input to a quarter-wave line is opposite to the load.
2. If the load or end is shorted, an open is seen at the input.
3. An open produces maximum voltage and minimum current at the resonant frequency. Therefore, a shorted quarter-wave line (open input) acts like a high impedance or parallel-resonant circuit. Signals at the resonant frequency are rejected.
4. If the load or end is open, a short is seen at the input.
5. A short produces maximum current and minimum voltage at the resonant frequency. Therefore, an open quarter-wave line (shorted input) acts like a low impedance or series-resonant circuit. Signals at the resonant frequency are passed.

APPLICATIONS OF RESONANT TRANSMISSION LINES

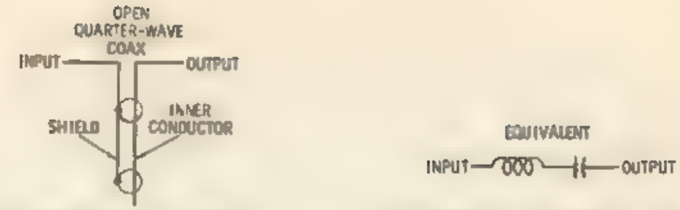
Some typical applications of resonant lines are shown in Figs. 5-6 through 5-9. In each case, the resonant circuit is made up of 72-ohm coaxial cable, cut to an exact quarter-wave at the resonant frequency.

In Fig. 5-6A, the coaxial cable is used in place of a coil and capacitor as a parallel-resonant circuit. When the cable is short-circuited at its far end, the impedance at the open end is extremely high. Fig. 5-6B shows the equivalent circuit. At the resonant frequency, it will have a very high impedance, but will have a low impedance at other frequencies.



(*A*) *Physical connections.* (*B*) *Equivalent electrical circuit.*

Fig. 5-6. Shorted quarter-wave coaxial line shunting signal path.



(*A*) *Physical connections.* (*B*) *Equivalent electrical circuit.*

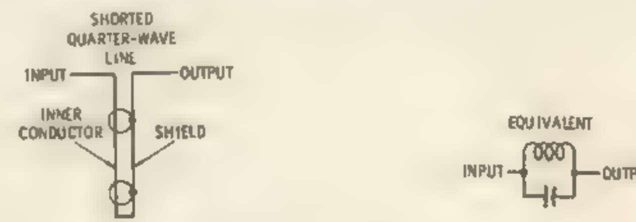
Fig. 5-7. Open quarter-wave coaxial line in series with signal path.

When the far end of the quarter-wave section of coaxial cable is open, as shown in Fig. 5-7A, a series-resonant circuit is formed. Its equivalent circuit is shown in Fig. 5-7B. At its resonant frequency, this line will have a very low impedance, but will have a high impedance at other frequencies. Fig. 5-8

(*A*) *Physical connections.* (*B*) *Equivalent electrical circuit.*

Fig. 5-8. Open quarter-wave coaxial line shunting signal path.

shows how both types of series-resonant circuits are shunted across the signal path to short-circuit signals at the resonant frequency. A parallel-resonant circuit can be used in series with the signal path, as shown in Fig. 5-9, to block passage of signals at the resonant frequency.



(*A*) *Physical connections.* (*B*) *Equivalent electrical circuit.*

Fig. 5-9. Shorted quarter-wave coaxial line in series with signal path.

RESONANT CAVITIES

Resonant cavities, which are a form of coaxial transmission line, may be cylindrical, spherical, or cubical in shape. Or they may be in the form of a doughnut, cylindrical ring, or rectangle (like most uhf television receiver front-end sections). Such a cavity is like a coaxial cable with both ends closed off. In a resonant cavity, such as the one shown in Fig. 5-10, which has a center conductor (the cavity), the resonant frequency is determined by the length of the center conductor and the value of C.

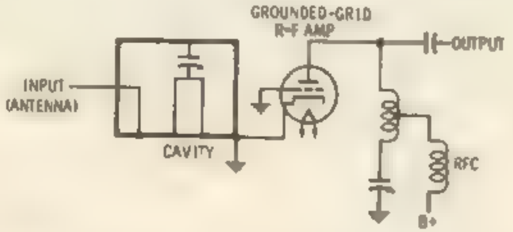


Fig. 5-10. Resonant cavity used with grounded-grid r-f amplifier.

Some cavities are tuned by a capacitive or inductive tuning slug whose position with respect to the electric and magnetic lines of force determines the frequency within the limits set by the dimensions of the cavity.

One of the advantages of a resonant cavity is that it contains the energy within the cavity so that radiation is minimized. Energy can be fed into or out of the cavity by means of a loop or probe. (See Fig. 5-11.) As shown in Fig. 5-11A, it is possible to couple directly to the inner conductor. Fig. 5-11B shows typical capacitive coupling. The most practical means of coupling to a uhf resonant cavity is by means of an inductive loop, as shown in Fig. 5-11C.

There are no basic electrical differences between resonant cavities and parallel lines. However, the physical characteristics are quite different. One of the problems in parallel transmission lines is that there must be some form of electrical lead between the vacuum-tube elements and the line itself. These leads present a certain amount of inductance to the circuit. Since the lead is in series with the signal path, the lead can act as an r-f choke and attenuate the signal. Special-purpose tubes have been developed wherein the active tube elements (cathode, plate, and grid) all fit within the resonant cavity, and connect directly to the inner and outer conductors as re-

(A) Direct coupling.

(B) Capacitive coupling.

(C) Inductive coupling.

Fig. 5-11. Methods of coupling energy in and out of a resonant cavity.

quired. One such tube is known as the *lighthouse tube*. Here, the tube elements terminate in concentric discs that fit directly into the cavity elements. The lighthouse tube is discussed further in Chapter 7, since its primary function is that of an oscillator.

RESONANT-LINE TRANSFORMERS

A resonant transmission line can be used to provide transformer action. As previously discussed, a quarter-wave line inverts the load. If the load is a short (low impedance), the input will be an open (high impedance). If the same quarter-wave line is terminated in a low impedance (but not a short), the input will be a high impedance (but not the infinite impedance of an open). Likewise, if the line is terminated in some form of high-impedance load (but not an open), the input will see a low impedance (but not a short or zero impedance).

This principle can be used to match a high impedance to a low impedance, as shown in Fig. 5-12. This type of line is known as a *matching section*. With all matching sections, there

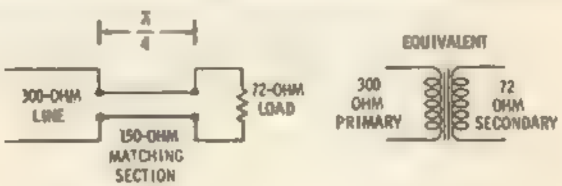


Fig. 5-12. Impedance matching with an open quarter-wave line section.

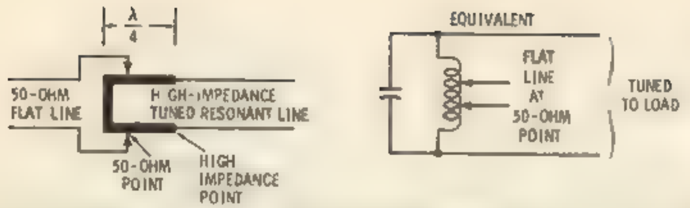


Fig. 5-13. Impedance matching with a shorted quarter-wave line section.

is a fixed relationship between the input/output impedances and the characteristic impedance of the line itself.

It is also possible to match a flat untuned transmission line to a tuned resonant line by means of a matching section of line. As shown in Fig. 5-13, the high-impedance tuned resonant line is connected to the high-impedance end of the line section, while the flat line is tapped near (but not exactly at) the shorted end of the section.

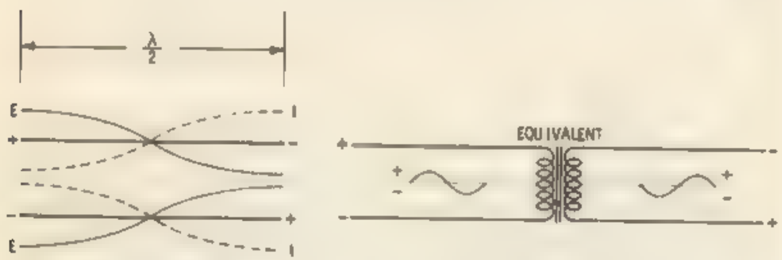


Fig. 5-14. Phase shifting with an open half-wave line section.

A half-wave section of line can be used to shift the phase of signals without changing the impedance at either the input or output. As shown in Fig. 5-14, there is a 180-degree phase shift along a half-wave line. This is the same as the polarity reversal that occurs through a transformer.

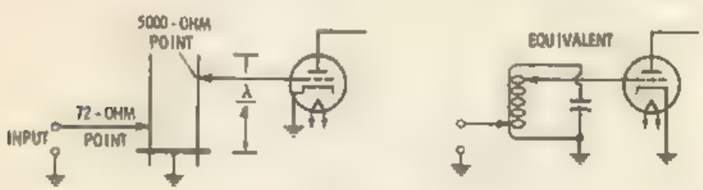


Fig. 5-15. Matching input-circuit impedances with a shorted quarter-wave line.

A shorted quarter-wave line is often used to match impedances, as shown in Fig. 5-15. Here, the input is tapped at some low impedance (such as 72 ohms to match a coaxial cable), while the output is tapped at a high-impedance point (such as 5000 ohms to match the grid). Both the input and output can be moved along the line to the desired impedance point.

RESONANT-LINE INSULATORS

It is possible to use a resonant line to insulate or isolate two points so far as r-f signals are concerned, but at the same time provide a d-c current path between the two points. An example of this is shown in Fig. 5-16. The metal rods used as supports

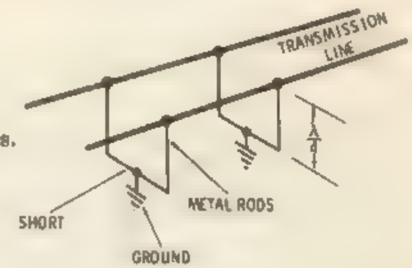


Fig. 5-16. Resonant-line insulators.

for the transmission line are cut to one-quarter wavelength of the signals passing along the transmission line. Since these rods are shorted, they present zero impedance at the short, but high impedance at the transmission-line end. Therefore, signals (at the resonant frequency) passing along the transmission line cannot pass through the metal rods to ground. However, any d-c currents present in the transmission line (such as a bolt of lighting) will pass from the transmission line to ground through the rods.

This type of metal insulator can also serve as a form of filter. For example, all of the even harmonics of the resonant frequency passing through the transmission line will be short-circuited since they will see a low impedance. Conversely, the odd harmonics will see a high impedance and will pass through the transmission line from source to load without effect.

RESONANT-LINE FILTERS

There are two basic approaches to using resonant lines as filters. These are shown in Figs. 5-17 and 5-18. In both cases,

the filter passes the fundamental frequency, plus all of the odd harmonics, but rejects all of the even harmonics.

In Fig. 5-17, the shorted quarter-wave line is in parallel across the transmitter output. At the fundamental resonant frequency, the line appears as a high impedance. Therefore, signals pass from the transmitter to the antenna without attenuation. If the transmitter signal contains a harmonic that is three times the fundamental, the quarter-wave line then becomes a three-quarter wave line, and still appears as a high impedance to the third harmonic. If the harmonic were the fifth, the line would then appear to be 1¼ wavelengths, and would still present a high impedance to ground. This same condition holds true for any odd harmonic. However, if the harmonic were even, say twice the fundamental, then the quarter-wave line becomes a half wave, and appears as a short between antenna and ground. The same is true at the fourth harmonic, where the line becomes a full wave; at the sixth harmonic, where the line becomes 1½ wave, etc.

Fig. 5-17. Resonant-line filtering with a shorted quarter-wave section.

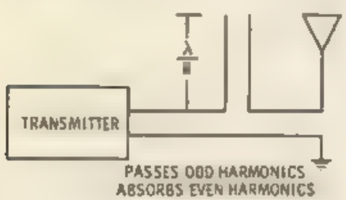


Fig. 5-18. Resonant-line filtering with an open quarter-wave section.

In Fig. 5-18, the open quarter-wave line is in series with the transmitter output. At the fundamental resonant frequency or at any odd harmonic, the line appears as a short or low impedance. Therefore, signals pass from the transmitter to the antenna without attenuation. If the transmitter signal contains a harmonic that is twice the fundamental, the quarter-wave line then becomes a half wave and appears as an open or high impedance. This high impedance absorbs most of the signal, and attenuates the transmitter output to the antenna.

RESONANT TUNING STUBS

One common use for a resonant line is that of a tuning stub for antennas. These stubs are usually used with half-wave dipoles such as uhf television antennas, and are connected in parallel with the antenna. Their effect is to change the electrical length of the antenna, and thus the resonant frequency, without changing the physical length. This permits a better match between the line and antenna, as well as extending the useful frequency range of the antenna.

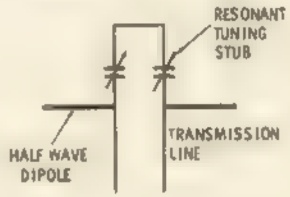


Fig. 5-19. Resonant-line tuning stub.

Either a shorted quarter-wave or open half-wave stub can be used. However, the shorted quarter-wave is more popular since the short minimizes radiation losses. The stubs can be tuned by varying their physical length, or by changing their electrical length with variable capacitors.

A typical tuning stub is shown in Fig. 5-19. Such a stub combines with the resonance of the antenna and transmission line. The resonant frequency is changed by varying the trimmer capacitors. The use of trimmer capacitors is, in most cases, more practical than a movable short.

RESONANT-LINE BALANCE DEVICES

Resonant lines can be used to achieve a match between a balanced line (such as twin-lead or open-wire transmission line) and unbalanced line (such as coaxial line). Not only must a balance-to-unbalance condition be accomplished without loss,

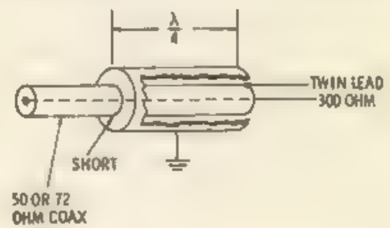


Fig. 5-20. Quarter-wave balun.

but the impedances must also be matched. Such a resonant line is known as a *balun*, an acronym from the term BALance-to-UNbalance.

If the input is unbalanced, such as a coaxial line, then a quarter-wave balun can be used, as shown in Fig. 5-20. The

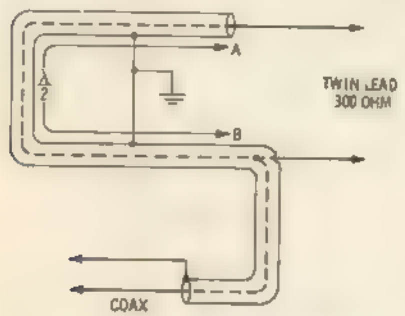


Fig. 5-21. Half-wave balun.

coax end of the balun is shorted to the coax outer conductor, and is connected to ground. The opposite end of the balun is open. Since the input and output of a balun are inverted, the coax end has a low impedance (to match a low-impedance value such as 50 or 72 ohms), while the twin-lead end has a high impedance (such as 300 or 450 ohms). This achieves the impedance match. The balance-to-unbalance condition is achieved by the fact that the low-impedance end of the balun is grounded, placing each parallel wire of the twin-lead above ground simultaneously.

It is also possible to use a half-wave balun to obtain the same results. As shown in Fig. 5-21, the outer coax conductor is connected to ground in the usual manner. Therefore, both points A and B are above ground, producing a balanced output. However, point B is one-half wave removed from point A. Thus, each side of the line sees the same signal, but shifted 180 degrees in phase. In effect, the half-wave balun converts a single-ended input to a push-pull output.

6

Microwaves—The High End of UHF

As established in Chapter 1, the uhf band extends from 300 to 3000 MHz. The frequency range from about 1000 to 3000 MHz (actually anything above 1000 MHz) is known as the microwave region, since the waves are quite short. A full wave at 1000 MHz is about one foot, while a full wave at 3000 MHz is approximately four inches. Radio waves at these frequencies behave somewhat like light waves. Also, they require special handling with respect to transmission lines, attenuation, resonant circuits, and oscillator circuits. The microwave region is used primarily for radar and related types of equipment. However some television relay systems use microwaves at frequencies of about 2000 MHz. With advances in technology, it is quite possible that microwaves will be used to a greater extent in the future.

MICROWAVE TRANSMISSION LINES

While it is possible to transmit microwaves along a conventional transmission line such as a coaxial cable, it is not practical. Because of the skin effect previously discussed, high-frequency radio waves tend to travel on the outside of a conductor. The higher the frequency, the nearer the skin they travel. This means that the conducting area decreases as the frequency increases. (See Fig. 6-1.) Since the resistance increases as the conducting area decreases, high frequencies produce high resistance. This is not much of a problem with the large outer conductor of a coax cable, but the small surface of the coax inner conductor becomes an extremely high resistance when radio waves approach or exceed 1000 MHz in frequency.

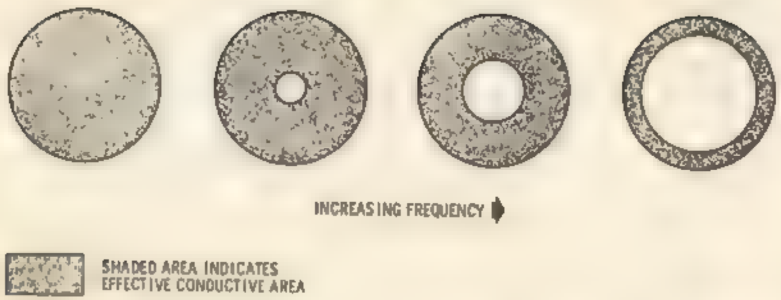


Fig. 6-1. Conductor cross-sections illustrating "skin effect" as frequency is increased.

This problem is overcome by means of hollow transmission lines known as *wave guides*, which are used instead of coaxial cables in microwave work. As shown in Fig. 6-2, a wave guide is made up of two parallel strips of metal, with two additional strips at the top and bottom to enclose the radio waves in conducting metal. Since the wave guide is hollow, all of the conducting area is at the surface or skin; there is no small inner conductor as in a coax. Therefore, the radio waves (which travel on the skin only) have maximum conducting area and minimum resistance or loss. Also, since it is not necessary to support an inner conductor with a solid dielectric, there is no dielectric loss.

A wave guide, like a coaxial cable, has little radiation loss such as would be present in a simple two-wire transmission line. A wave guide has a further advantage in that the spacing between conductors is about twice that of a coaxial cable. This means that a wave guide will withstand a higher voltage before there is a breakdown between the conductors. Consequently, a wave guide can handle higher power than coaxial cable.

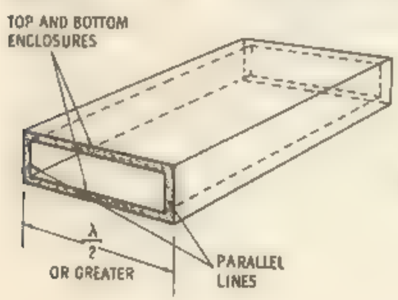


Fig. 6-2. Wave-guide construction.

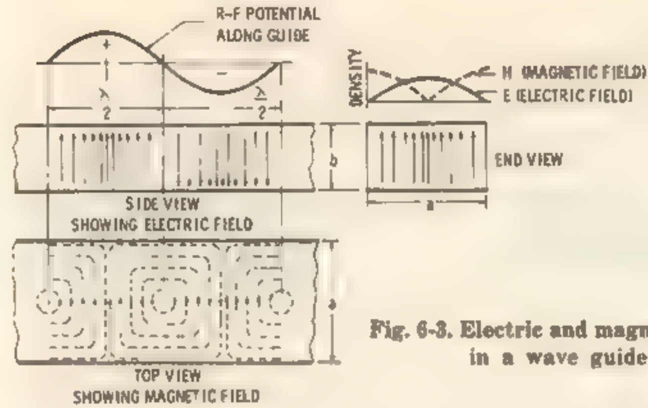


Fig. 6-3. Electric and magnetic fields in a wave guide.

It may be wondered why wave guides are not used more extensively at lower frequencies since they have so many advantages over conventional transmission lines. For a wave guide to operate correctly, the longer physical dimension must be equal to or greater than a half-wave. If not, the radio waves will be attenuated to almost zero. In effect, there is a cutoff frequency below which the radio waves are stopped for any given dimension of wave guide. For example, a half-wave at 300 MHz (the low end of the uhf band) would be about twenty inches. If the longer dimension of the wave guide were less than 20 inches, all signals below 300 MHz would be cut off.

Fig. 6-3 shows the relationship between the electromagnetic and electrostatic fields within a rectangular wave guide. Both the electric and magnetic waves are contained within the wave guide, although they are at 90-degree angles to each other, and at 90-degree angles with respect to the path of radio waves passing along the wave guide. The density of the electric fields is maximum at the center of the wave guide, while the magnetic fields are maximum at the sides.

WAVE GUIDES AS REACTIVE AND RESONANT CIRCUITS

It is possible to make a wave guide act as a resonant circuit or a reactive component by placing metal plates within the wave guide. As shown in Fig. 6-4, an inductive reactance is formed when plates are placed across the short side of the wave guide. When plates are placed across the long side of the wave guide (Fig. 6-5), a capacitive reactance is introduced into the wave guide. Either way, the plates cause a portion

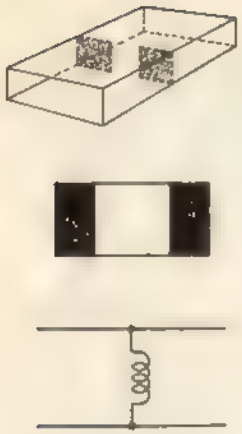


Fig. 6-4. Adding inductive reactance plates to a wave guide.

of the radio waves to be reflected and set up standing waves. Also, the amount of reactance (inductive or capacitive) is determined by the spacing between the plates. An increased space causes an increased reactance.

As shown in Fig. 6-6, a parallel-resonant circuit is formed with a combination of plates. The resonant point or frequency is determined by the size of the opening.

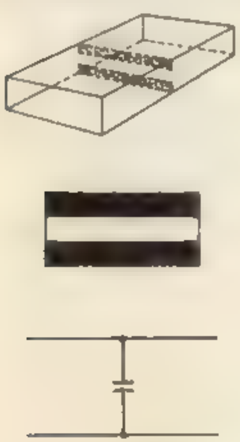


Fig. 6-5. Adding capacitive reactance plates to a wave guide.

ATTENUATING SIGNALS IN WAVE GUIDES

There are two basic methods for attenuating signals in a wave guide. The simpler method is to place a conductive plate

Fig. 6-6. Adding resonant circuit plates to a wave guide.

across the wave guide, as shown in Fig. 6-7. As the plate closes off the interior of the wave guide, less radio energy passes and the signal is attenuated. The signal can be attenuated fully if the interior of the wave guide is closed off completely. Although this method is effective, it produces undesired standing waves in the wave guide. Any partial or complete short across the conducting surfaces of a wave guide will produce some reflection of energy. This reflected energy, while it produces the desired attenuation, also produces standing waves since the reflected waves will be both in and out of phase with the transmitted waves.

When it is desired to keep standing waves to an absolute minimum, an absorption type of attenuator is used in wave guides. (See Fig. 6-8.) The basic element of such an attenuator is a resistance card which passes through a slot in the wave guide. Both sides of the card are coated with a conductive material which, when inserted through the slot, is parallel to the electrical fields of the radio waves passing through the wave-

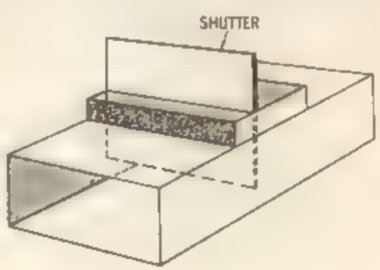


Fig. 6-7. Shutter-type wave-guide attenuator.

guide. The conductive surfaces absorb a portion of the energy, thus attenuating the signal. The position of the resistance card is determined by a calibrated dial. The size of the card, the characteristic of the card material, and the position of the card within the wave guide determine the amount of attenua-

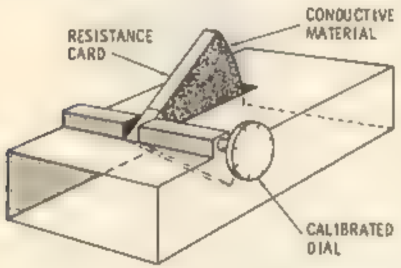


Fig. 6-8. Absorption-type wave-guide attenuator.

tion. Although this method still causes some reflection of energy, the reflection is at a minimum since the conducting surface of the card is in parallel with the conducting surfaces of the wave guide.

INTRODUCING OR REMOVING POWER IN WAVE GUIDES

There are several methods for coupling energy in wave guides. For maximum transfer of energy, such as when a microwave oscillator is to be coupled to an antenna through a wave guide, the oscillator is built into a section of wave guide. In turn, this wave-guide section is coupled directly to the antenna wave guide, just as two sections of pipe might be joined. However, it is often necessary to introduce power into a wave guide, or to remove power, through a coaxial cable.

As shown in Fig. 6-9, energy is introduced by means of a probe, which is actually a continuation of the coaxial cable in-

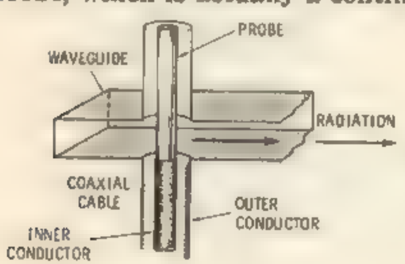


Fig. 6-9. Coupling energy into a wave guide.

ner conductor. The outer conductor of the coaxial cable is in contact with the top and bottom of the wave guide, but not in contact with the conducting sides. The inner conductor acts like an antenna, radiating the signal in all directions. However, since the signal is enclosed in all directions, it passes down the wave guide in the desired direction.

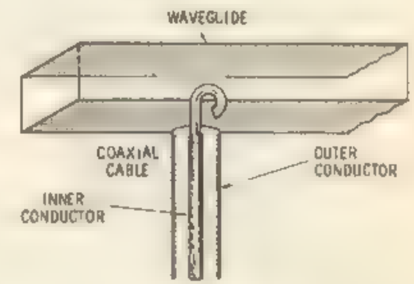


Fig. 6-10. Removing energy from a wave guide.

The coaxial cable inner conductor is bent to form a loop, as shown in Fig. 6-10, when energy is to be taken from a wave guide. Usually, the loop is connected to the top or bottom of the wave guide, but not to either of the conducting sides. Any energy within the wave guide is picked up by the loop and is transmitted through the coaxial cable.

WAVE GUIDES AS FILTERS

A particular frequency can be filtered from a wave guide by adding a section of wave guide, as shown in Fig. 6-11. The added section, known as a fixed-tuned stub, must be a quarter-wave long at the resonant frequency to be filtered out. It also must be shorted at the load end and open at the input end. The short is reflected as an open, or a high impedance. This serves to absorb the energy, thus filtering out signals of that resonant frequency from the wave guide. The same principle can be used where the quarter-wave stub is tuned by means of a plunger.

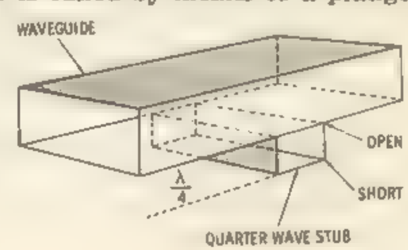


Fig. 6-11. Wave-guide filter.

This permits the filter to be adjusted so as to remove signals of various resonant frequencies.

MATCHING WAVE-GUIDE SECTIONS

Wave guides of different sizes can be matched by means of an intermediate matching section, as shown in Fig. 6-12. However, such an arrangement often results in reflected waves due to the abrupt change in size and impedance. Where one size

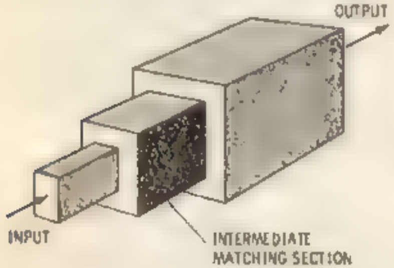


Fig. 6-12. Matching wave-guide sections with an intermediate section.

of wave guide must be matched to another size with a minimum of reflections, the flared matching section shown in Fig. 6-13 is used. The gradual change in dimensions does not present any shorts or partial shorts to the signals passing through the wave guide.

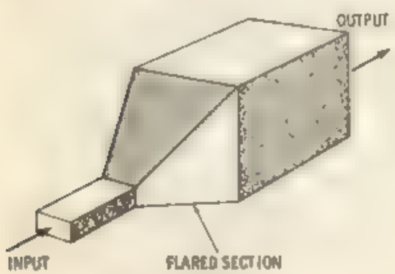


Fig. 6-13. Matching wave-guide sections with a flared section.

RESONANT CAVITIES

A resonant cavity is essentially a tuned, or tunable, section of wave guide that acts like a resonant circuit. The size of the cavity determines the resonant frequency. Resonant cavities are made in various shapes. However, their operation is best understood when the cavity is considered to be rectangular.

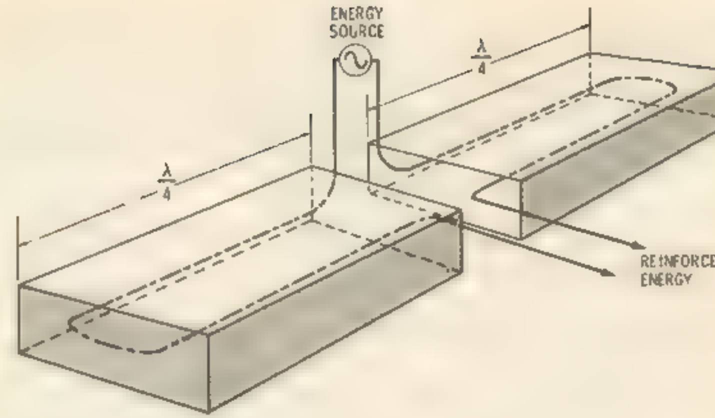


Fig. 6-14. Basic resonant cavity.

Assume that the cavity consists of two identical rectangular sections, as shown in Fig. 6-14. Both sections are one-quarter wave long at the desired resonant frequency, and both are shorted at the ends. Any r-f signals generated at the center point will travel down the rectangular sections, hit the short, and be returned. Since each section is a quarter-wave long, the returning energy will be returned at the same time, and will be reinforced. Therefore, the cavity acts like a parallel-resonant circuit, with the resonant frequency being determined by the length of the rectangular sections.

Resonant cavities could be used at lower frequencies. However, their physical size makes this impractical. For example, two quarter-wave sections at 300 MHz would be about twenty inches long. Therefore, resonant cavities are usually limited to the microwave region. At 3000 MHz, two quarter-wave sections would be about two inches long.

Although it is easier to understand the operation of a rectangular resonant cavity, a cylinder or cylindrical ring shape is used most often. The exact shape of a resonant cavity is usually determined by the equipment with which the cavity will be used. For example, the klystron (discussed in a later section) is a microwave tube using two built-in resonant cavities. Normally, these cavities are cylindrical rings arranged so that the cathode-to-anode electron flow is through their center.

TUNING RESONANT CAVITIES

There are three basic methods for tuning resonant cavities. The most obvious method is to vary the length of the cavity,

since frequency depends on cavity dimensions. In practice, this works well with cylindrical or rectangular cavities, but is not practical for cylindrical rings. A typical tuned cavity (cylinder or rectangle) with an adjustable plunger is shown in Fig. 6-15. Such an arrangement is often used with a slotted transmission line, which is discussed in Chapter 10.

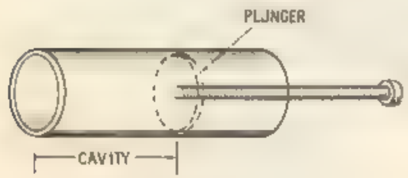


Fig. 6-15. Cylindrical resonant cavity tuned by a plunger.

It is also possible to tune a cavity by varying the capacitance between the sides of the cavity. Since a resonant cavity is essentially a section of wave guide or transmission line, any changes in capacitance between the lines or conductors will change the frequency, just as will a variation of capacitance in a conventional l-c circuit. An increase in capacitance decreases the resonant frequency, and vice versa. Since it is not too practical to vary the spacing in a cavity, the capacitance is varied by means of a screw-type capacitor inside the cavity. (See Fig. 6-16.) In effect, the capacitance is varied as the screw is turned. In some applications, the screw is driven by a dial which is related to a frequency scale. This principle is often used in microwave frequency meters.

The third method of tuning a resonant cavity involves changing the density of the electric and magnetic waves within the cavity. As previously discussed, both electric and magnetic waves are contained within a wave guide or cavity. The density of the electric fields is maximum at the center of the wave guide or cavity, while the magnetic fields are maximum at the sides. If a metal object, such as a steel ball, is placed in the center, where the electric fields are maximum, the density of the

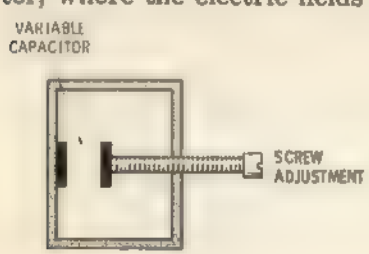


Fig. 6-16. Rectangular resonant cavity tuned by a capacitor.

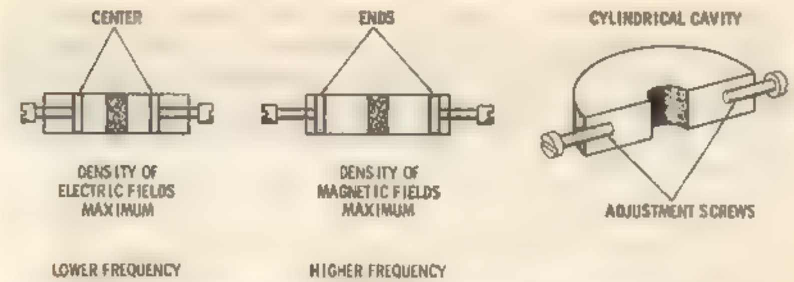
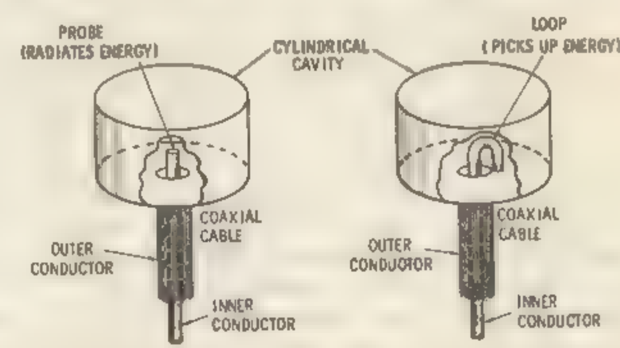


Fig. 6-17. Cylindrical resonant cavity tuned by adjustment screws.

lines is changed so that the cavity frequency is lowered. If the same object is placed near the outer end or other diameter of the cavity, where the magnetic lines are strongest, the frequency will be increased. In practice, this changing of frequency by varying the density of the waves is accomplished with adjustable screws or slugs, as shown in Fig. 6-17.

TRANSFER OF ENERGY IN RESONANT CAVITIES

There are three basic methods for coupling energy in a resonant cavity. The first two methods shown in Fig. 6-18 are similar to the method used in wave guides. In one case, energy can be introduced by means of a probe, which is a continuation of a coaxial cable inner conductor. This conductor acts like an antenna, radiating the signal in all directions. In the other case, the conductor is bent to form a loop when energy is to be taken from the cavity. Any energy within the cavity is picked up by the loop and is transmitted through the conductor.



(A) Probe coupling. *(B) Loop coupling.*

Fig. 6-18. Energy coupling in resonant cavities.

A special method is used with klystron tubes. As shown in Fig. 6-19, the cathode-to-anode electron flow passes through holes at the center of the cavity. As discussed in a later section, this develops energy in the cavity at the resonant frequency of the cavity. The energy can then be extracted from the cavity by a pickup loop.

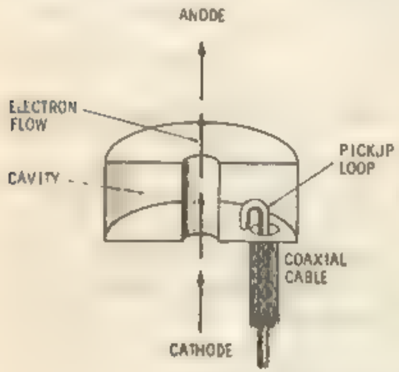


Fig. 6-19. Energy coupling in a klystron cavity.

KLYSTRON TUBES

The klystron is one of the most commonly used tubes in microwave work. Its operation is based on the principle of *velocity modulation*. One of the factors that limits the maximum or ultimate frequency of radio waves is the transit time of electrons from the cathode to the anode of vacuum tubes. For example, if it takes a given amount of time for electrons to move from cathode to anode, it is impractical to use that tube as an oscillator at a frequency higher than that given time. If the transit time were one second, the tube could not oscillate above 1 Hz. If the time were one microsecond, the maximum frequency limit would be 1 MHz, and so on. (Actually, there are other factors that affect transit time). Transit time is determined primarily by the spacing between cathode and anode, and by acceleration of the electrons. Assuming that the spacing is fixed at some limit imposed by the voltage differential, the transit time is controlled by acceleration of the electrons. If electrons can be speeded, the frequency can be increased. Therefore, the frequency of r-f energy can be controlled by controlling the velocity or acceleration of electron flow. If the electrons can be made to move past a point at a given velocity, energy can be taken from that point, and this energy will be at a frequency determined by the acceleration.

The basic operation of a klystron is shown in Fig. 6-20. As in a conventional vacuum tube, the electrons pass from cathode to anode (identified as the collector plate) through an accelerating grid. Acceleration of the electron stream is controlled by the amount of voltage on the accelerator grid. There-

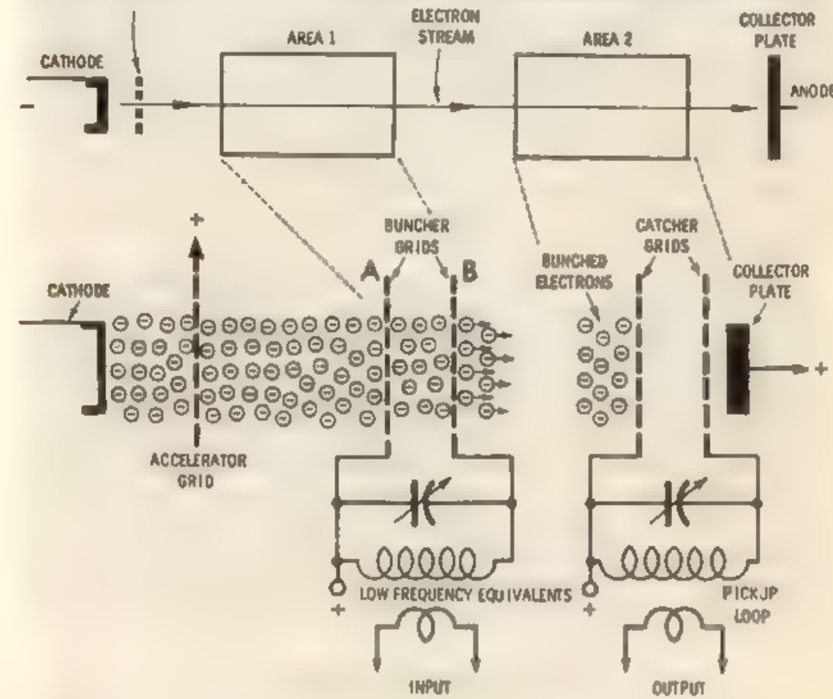


Fig. 6-20. Basic operation of a klystron tube.

fore, overall control of the klystron frequency is obtained by varying the accelerator voltage. Operation of the klystron to produce a specific frequency is determined by the buncher and catcher circuits.

As shown, the low-frequency equivalents of the buncher and catcher circuits are parallel-resonant circuits with grids placed in the electron stream. The buncher controls the electron-stream acceleration at some given frequency, while the catcher extracts energy from the electron streams at that frequency.

As the electron stream passes the A and B grids of the buncher parallel-resonant circuit, a voltage differential is developed across the grids. The capacitor is charged, and then discharges through the inductance (as in any parallel-resonant

circuit) at a frequency determined by the circuit values. This makes the A and B grids alternately positive and negative. When grid A is positive, the electrons are speeded up. As these electrons approach grid B, they are slowed down. Therefore, the electrons are bunched and are at the resonant frequency of the buncher circuit. When these bunched electrons arrive at the catcher circuit, they produce the same effect, except that they are reinforced since they have been bunched at the resonant frequency of the catcher. Consequently, the klystron produces some amplifier action, as well as oscillation. If the catcher is coupled to an external circuit, part of the energy across the parallel-resonant circuit can be taken from the catcher, just as with the parallel circuit of a transmitter or oscillator tank.

In practice, the buncher and catcher parallel circuits are replaced with resonant cavities. The energy is extracted from the catcher by means of a probe or loop. In some klystrons, it is possible to inject a signal into the buncher so that it can be amplified and taken from the catcher. In others, part of the catcher output is fed back to the buncher to obtain oscillation. One of the unique features offered by a klystron is that, being a vacuum tube with built-in resonant circuits, it will function as a one-piece microwave oscillator. In practical applications, the frequency limits are set by cavity dimensions, while the frequency is controlled by adjustment of the accelerator grid voltage, or by cavity tuning, or both.

MAGNETRON TUBES

The magnetron tube is used in microwave work, where high power is required. Magnetrons were originally developed for use with radar, where they function as oscillator or transmitter tubes and are pulsed with potentials in the kilovolt range. Magnetrons use magnetic fields to change or bend the path of electrons so that the electrons will pass by a given point at a given speed.

Assume that there is a pickup loop at a given point, and that an electron stream passes this point in such a way that the beam moves toward the point and then away from it. The loop will take some energy, and this energy will alternate at the rate determined by the rate at which the stream passes and bends. Therefore, if the electron stream path can be controlled, so can the frequency.

The basic operation of a magnetron is shown in Fig. 6-21. As in a conventional tube, the electrons pass from cathode to

anode. In most magnetrons, the anode is in the shape of a circular ring, with the cathode at the center. Strong magnetic fields, usually supplied by a permanent magnet, are placed at right angles to the normal electron stream. Without any magnetic action, the electrons will move directly from cathode to anode by the shortest possible route. However, when an electron stream is placed within a magnetic field, it is attracted and repelled. Assume, as shown in the example of Fig. 6-21,

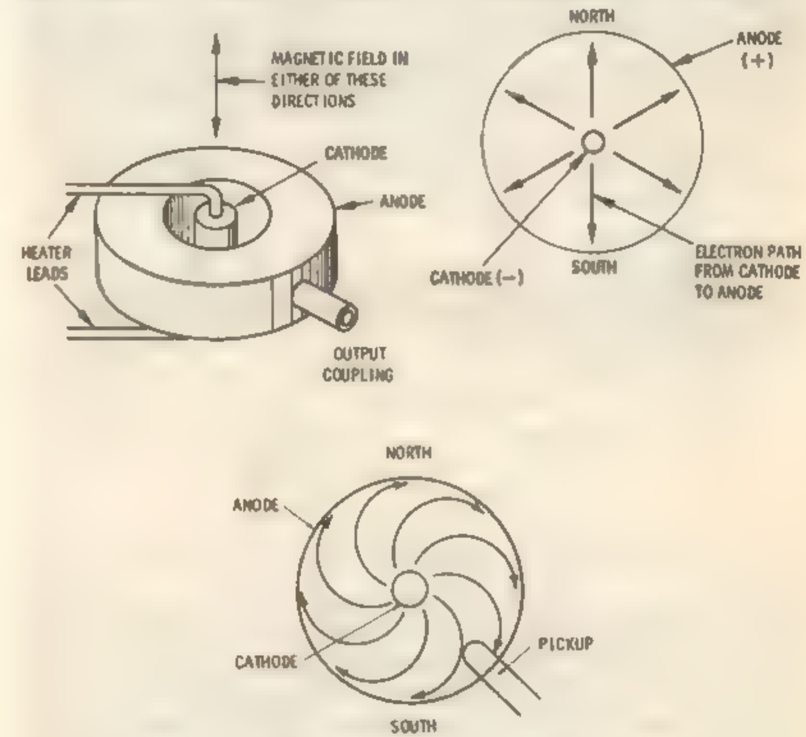


Fig. 6-21. Basic operation of a magnetron tube.

that the stream is attracted by the north pole and repelled by the south pole. The electron beam then bends toward the north pole, and follows a twisted path from cathode to anode. As the beam moves toward the pickup loop, it induces a voltage in the loop. The same is true when the beam moves away from the loop, except that the induced voltage is of the opposite polarity. Therefore, as the electron beam is bent, it induces an a-c voltage in the loop. If the beam is bent or twisted at an r-f rate, the induced voltage will be at radio frequencies. If the rate is at microwave frequencies, the pickup loop will have a micro-

wave output. This output can be coupled through a wave guide to an antenna, or to whatever circuit is desired. Again, magnetrons could theoretically be used at lower frequencies, but their size would be fantastic.

TRAVELING-WAVE TUBES

Although traveling-wave tubes are not used in microwave work exclusively, their operation is usually limited to the high end of the uhf spectrum. As shown in Fig. 6-22, a traveling-wave tube is made up of three basic components: (1) the electron gun, (a) a slow-wave structure or helix, and (3) a collec-

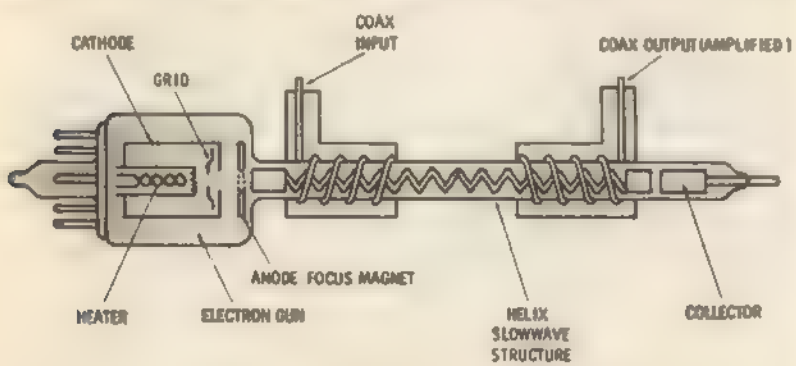


Fig. 6-22. Basic operation of a traveling-wave tube.

tor. A beam of electrons from the electron gun is sent to the collector through the slow-wave structure. An electromagnetic wave is propagated by the slow-wave structure. This propagation occurs at a velocity where the electron beam can be made to travel at the same speed. When this occurs, the electrons are continuously accelerated or decelerated by the waves. This results in bunching of the electrons at radio frequencies. The slow-wave structure can then take power from the bunched electrons as they move down the circuit. The longer the slow-wave structure, the more power can be taken. Therefore, the traveling-wave tube can act as an amplifier. Tube gain in decibels is approximately proportional to the tube length, as measured in wavelengths of the operating frequency. For example, if the slow-wave structure is three wavelengths long at the operating frequency, approximately 3-db gain can be obtained.

The bandwidth of a traveling-wave tube amplifier is usually quite large since there are no resonant circuits, as such, in-

volved. Therefore, traveling-wave tubes can be used as amplifiers for such devices as signal generators, which operate over a wide range. The range of frequencies where the slow-wave velocity is nearly constant determines the bandwidth.

A popular method of propagating electromagnetic waves along the electron beam is by means of a helix coil. A helix will provide the highest gain per unit of length, plus the greatest bandwidth. However, there are limitations. A helix is not too satisfactory where there is high electron velocity, since there is some tendency toward oscillation.

Focusing systems for the electron beam are required with most traveling-wave tubes. Magnetic focusing is used most often. Sometimes the magnetic field can be supplied by a permanent magnet or a series of permanent magnets. In other cases, the magnetic focusing field must be provided by a solenoid.

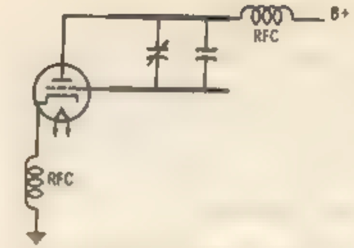
7

UHF Oscillator Circuits

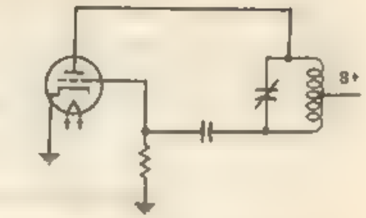
Many of the oscillator circuits used at lower frequencies are also used in uhf work. However, the resonant circuits for these oscillators are made up of transmission lines rather than the conventional coil-capacitor tank circuits. As discussed in Chapter 5, this is necessary since uhf requires inductance-capacitance combinations nearly impossible to achieve with conventional coils and capacitors. Consequently, parallel-line or coaxial-tank circuits are used for uhf. This chapter describes how such tanks are used with the various basic oscillator circuits, and shows both the uhf version of the circuit and the low-frequency equivalent.

ULTRA-AUDION OSCILLATOR

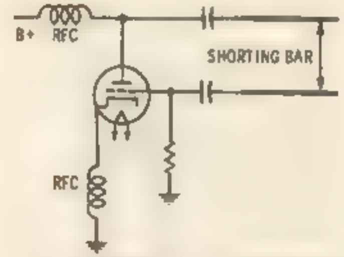
Below the microwave region (1000 MHz), the ultra-audion circuit is the most popular oscillator in uhf work. Practically all uhf television receivers use some form of ultra-audion circuit as a local oscillator. This circuit (Fig. 7-1) will work equally well with parallel lines or coaxial tanks, and can be shunt fed or series fed. The parallel-line or coaxial-tank circuit is connected between the grid and plate. This provides the 180-degree phase shift necessary to sustain oscillation. In most applications the parallel or coaxial lines are cut slightly shorter than is necessary for self-resonance (less than a quarter wave), so they act as an inductance. The capacitance is supplied by the vacuum-tube interelectrode capacitance, as well as by the trimmer and/or tuning capacitors.



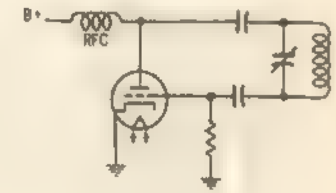
(A) Series-fed parallel-line oscillator.



(B) Low-frequency equivalent of (A).



(C) Shunt-fed parallel-line oscillator.

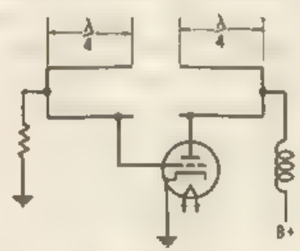


(D) Low-frequency equivalent of (C).

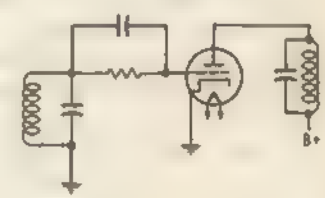
Fig. 7-1. Typical ultra-audion circuits.

TUNED-PLATE, TUNED-GRID OSCILLATOR

The tptg circuit, popular many years ago as a variable-frequency oscillator for lower-frequency applications, can be used effectively in uhf. As shown in Fig. 7-2, the low-frequency grid and plate tank circuits are replaced by quarter-wave transmission lines with a shorting bar to provide tuning. Conventional



(A) Ultrahigh-frequency circuit.



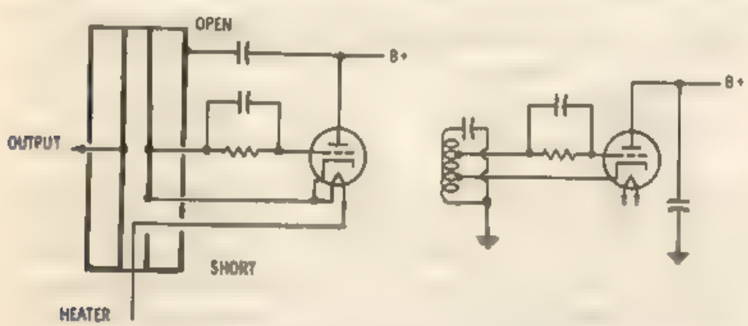
(B) Low-frequency equivalent.

Fig. 7-2. Tuned-plate, tuned-grid oscillator.

grid-leak bias is used. The tube plate is connected to its B+ voltage supply through an r-f choke. Since the transmission lines are a quarter-wave long and are shorted at the supply end, they present a high impedance to their respective grid or plate at the resonant frequency. Thus, they act as parallel-resonant circuits.

HARTLEY OSCILLATOR

A uhf version of the Hartley oscillator can be used with a tapped coaxial tank circuit. (See Fig. 7-3.) In the low-frequency equivalent, cathode current flows through a few turns



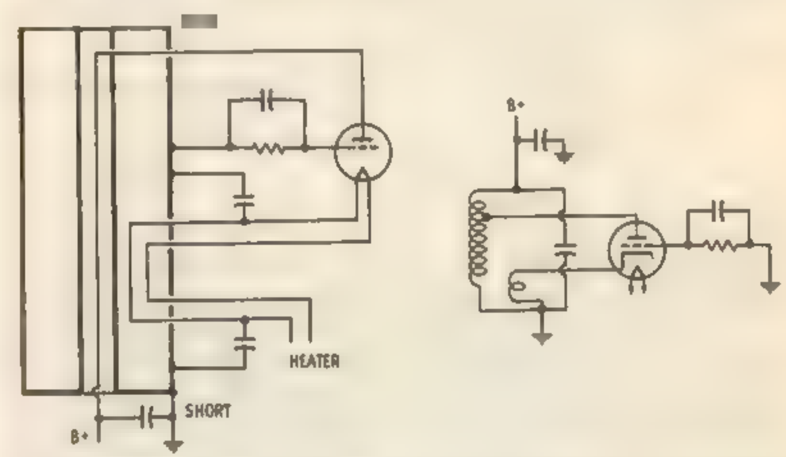
(A) Ultrahigh-frequency circuit. *(B) Low-frequency equivalent.*

Fig. 7-3. Modified Hartley oscillator.

of the tank inductance. This sets up lines of force which produce a voltage across the remaining portion of the tank. This potential is applied to the grid, causing a further change in cathode current. Since the feedback is positive, oscillation is sustained, and the frequency is determined by the tank-circuit values. In the uhf version, the cathode and grid are tapped to the inner conductor of a coaxial tank, while the plate is connected to the outer conductor. The coaxial tank is a quarter wave long and is shorted at one end. Both the inner and outer conductors are at ground potential as far as d-c is concerned. However, the cathode and grid are at different points along the inner conductor; consequently, there is an r-f potential difference between them. In addition, they are both 180-degrees out of phase in relation to the plate. This 180-degree phase shift provides the positive feedback necessary to sustain oscillation. Output is taken from a tap or probe within the coaxial line.

ARMSTRONG OSCILLATOR

A special tapped coaxial tank circuit can also be used to form an Armstrong oscillator. (See Fig. 7-4.) In the low-frequency equivalent, cathode current flows through a separate winding which is inductively coupled to the tank circuit. The low end of this winding and the grid are effectively at r-f ground. The high end of the tank circuit is directly coupled to



(A) Ultrahigh-frequency circuit. *(B) Low-frequency equivalent.*

Fig. 7-4. Modified Armstrong oscillator.

the tube plate and to B+. Any variation in the tank is inductively coupled to the cathode, and is reflected onto the grid as a form of positive r-f feedback, thus sustaining oscillation. In the uhf version, the heater is inductively coupled into the tank circuit. The low end of this coupling and the grid are effectively at r-f ground, since they are capacitor coupled to the outer conductor of the coaxial tank, which is at ground (both r-f and d-c ground). The plate is connected directly to B+, and is inductively coupled to the high end of the tank, since the B+ line passes through the inner conductor from the high end. The low end of the B+ line is effectively shorted to r-f ground through the capacitor. Therefore, the plate is 180 degrees out of phase with the grid. Any variation in the tank circuit is inductively coupled to the heater, and is reflected onto the grid as a form of positive r-f feedback, thus sustaining oscillation. Output is taken from an inductively coupled tap within the coaxial line.

USING COAXIAL LINES IN UHF OSCILLATORS

Coaxial lines can also be used in uhf oscillators to provide functions other than parallel-resonant tank circuits. An example of this is the use of coaxial lines to eliminate the need for filter circuits in the heater leads. Such filter circuits are

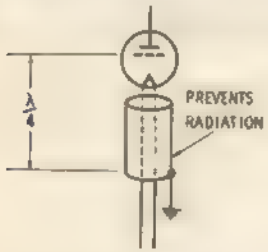


Fig. 7-5. Quarter-wave coaxial filter.

used to prevent r-f from passing from the tube or active circuit components back to the power supply, or to prevent radiation of r-f signals from the heater leads. Either a half-wave or quarter-wave coaxial line can be used. In either case, the two heater leads form the inner conductor. As shown in Fig. 7-5, the coaxial line is shorted one-quarter wavelength from the grids. Therefore, the grids see a high impedance, and no r-f will pass down the heater leads. In Fig. 7-6, the coaxial line is shorted one-half wavelength from the heater. Therefore, the heater sees a short to ground as far as r-f is concerned.

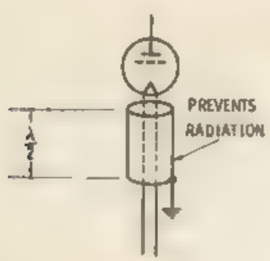


Fig. 7-6. Half-wave coaxial filter.

PUSH-PULL OSCILLATORS

Since a transmission line has two voltages 180 degrees apart, they can be used as tank circuits for push-pull oscillators. In the early days of uhf experimentation, a number of push-pull circuits were used as oscillators, since it was possible to obtain twice the power with two tubes. However, as improved uhf

tubes were developed, the need for push-pull oscillator circuits in uhf has been minimized. Present-day uhf receivers and transmitters rarely use push-pull oscillators, although push-pull amplifiers are used extensively in uhf transmitters. Some uhf signal generators (operating below 500 MHz) use a push-pull oscillator circuit. The same push-pull oscillator circuits used at lower frequencies can be duplicated at ultrahigh frequencies, with a transmission line acting as the tank circuit. Such an oscillator is shown in Fig. 7-7. It could serve as a low-

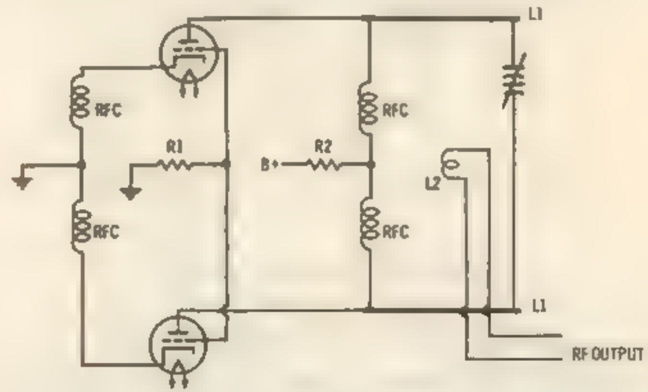


Fig. 7-7. Push-pull oscillator circuit.

power uhf transmitter. The circuit shown uses a pair of triodes as a grounded-grid, self-excited oscillator. It is tuned by C1 connected across two parallel rods which are slightly less than one-quarter wave long. The inductance of these rods combines with the capacitance of C1 and the tube interelectrode capacitance to form a parallel-resonant tank.

RING OSCILLATOR

The ring oscillator is a version of the basic push-pull circuit. Ring oscillators were used in early uhf work to take advantage of the power developed by four tubes. As shown in Fig. 7-8, four tuned transmission lines are used, together with four tubes operating as tuned-grid, tuned-plate oscillators. Any two of the tubes are in push-pull, such as V3 and V4, V2 and V3, V1 and V2, or V1 and V4. R3 and R4 are grid bias resistors, while R1 and R2 set the amount of plate current. Like most other push-pull circuits, the ring oscillator is no longer required for uhf, except in experimental work.

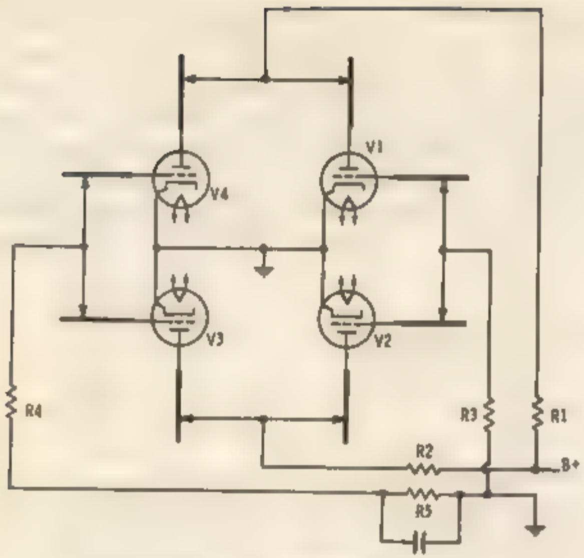


Fig. 7-8. Ring oscillator circuit.

THE LIGHTHOUSE TUBE

The lighthouse tube, mentioned in Chapter 5, is an example of a tube specifically developed as a uhf oscillator. The lighthouse tube was designed so that its active elements (grid, cathode, and plate) all fit within a resonant cavity and connect directly to the inner and outer conductors of the cavity as required. Useful as it was, the lighthouse tube has gradually been replaced by the klystron for microwave or near-microwave operation. Other similar special-purpose tubes are used for the lower portion of the uhf spectrum. Fig. 7-9 shows how a lighthouse tube can be integrated with a tuned resonant cavity. Lead inductance is kept to a minimum by means of contacting rings or discs. These lead rings or discs mate with corresponding inner and outer conductors of the resonant cavity. There are three coaxial cylindrical conductors. The outer conductor makes contact with the tube shell. The inner conductor contacts the tube plate. The intermediate conductor is connected to the tube grid.

The plate tank circuit consists of the grid and plate conductors. This plate tank is open-circuited at the end away from the tube. Plate voltage is applied to the plate tuning rod at the point where the plate line is shorted. R-f is prevented from flowing into the B+ supply by a high impedance that results

from the shorted quarter-wave section of line. The point where the plate line is shorted by the tuning rod is a quarter wave away from the open end.

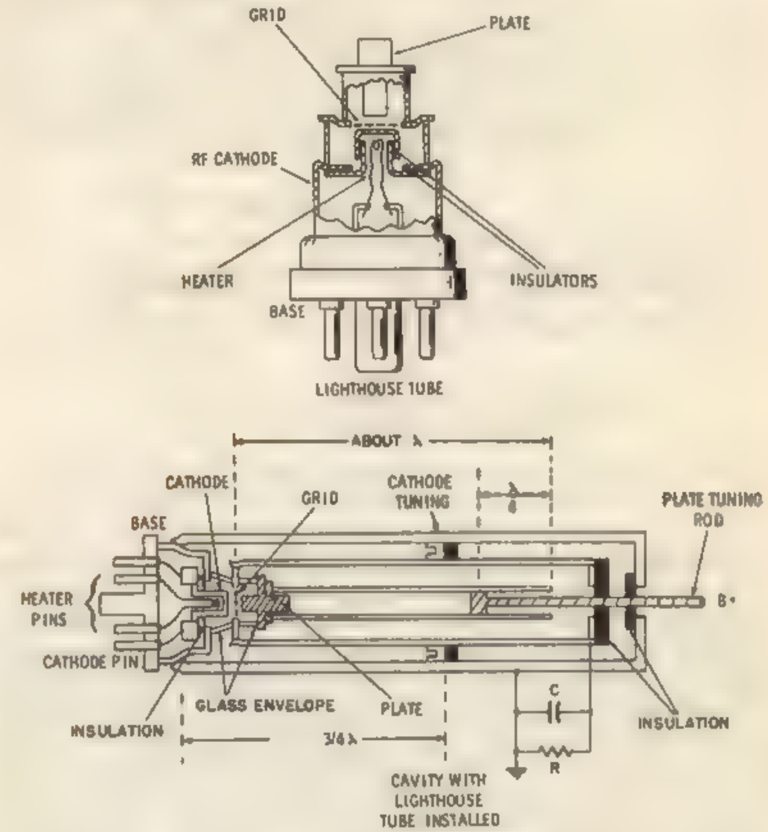


Fig. 7-9. Lighthouse tube oscillator.

Another tank circuit is formed by the grid conductor and by the outer conductor, which has an r-f connection to the cathode through capacitance. This cathode-grid tank is short-circuited at the end away from the tube by means of the cathode tuning plunger (at approximately three-quarter wavelength). Although this plunger provides an r-f short between the cathode and grid conductors (through capacitance), there is no d-c connection. The grid-leak bias path is formed by a conventional capacitor and resistor connected between the grid and cathode conductors.

Heater power for the tube, as well as a d-c path for the cathode, is provided by pins at the tube base.

OTHER SPECIAL-PURPOSE UHF OSCILLATOR TUBES

Since the development of the lighthouse tube, there have been a number of other special-purpose tubes (such as pencil triodes) which will work well at the lower portion of the uhf spectrum, and which can be integrated into a resonant-cavity circuit. Fig. 7-10 shows a tube which is an integral part of the

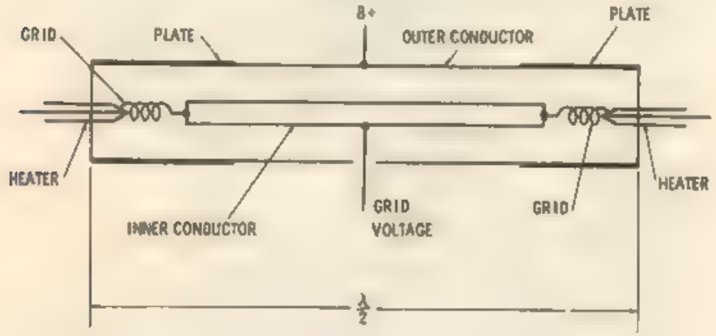
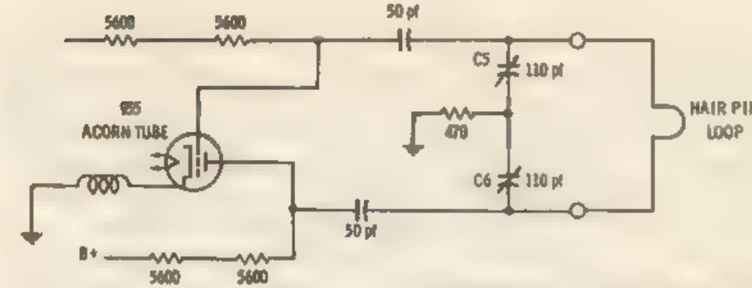


Fig. 7-10. Example of a vacuum tube as an integral part of a resonant cavity.

coaxial line or resonant cavity itself. The grid is a portion of the inner conductor, while a cylindrical plate is formed by the outer conductor. A heater is placed within the grid structure. Plate voltage is applied directly to the outer conductor. Grid voltage is applied to the inner conductor through a lead which is insulated from the outer conductor. In the example shown, there are two tubes separated from each other by a half wavelength. This half-wave is open-ended at both ends. Consequently, each tube sees an open-end half-wave, or a high-impedance circuit.

ACORN-TUBE OSCILLATORS

As discussed in Chapter 1, acorn tubes will operate satisfactorily at ultrahigh frequencies. Fig. 7-11 shows an example of such a tube being used as an oscillator for a grid-dip meter circuit. Here, a conventional Colpitts oscillator is used to provide operation up to about 1000 MHz. No resonant cavity or transmission line is used. However, the inductance in the tank circuit consists of a half turn (hairpin loop) of wire. As in typical Colpitts operation, oscillation takes place because the voltage developed across C5 and applied to the grid is 180 de-



Courtesy Measurements, Div. McGraw-Edison

Fig. 7-11. An acorn tube oscillator circuit used in a grid-dip meter.

grees out of phase with the voltage developed across C6 and applied to the plate.

OSCILLATOR DRIFT PROBLEMS

Drift is a major problem in uhf oscillators. This is especially true in variable-frequency oscillators such as uhf tv local oscillators. Drift is a result of temperature changes in the equipment during warm-up, and in the room during operation, that cause the oscillator to move off its proper frequency. Drift is minimized where crystal-controlled oscillators are used. Also, transistorized equipment has less of a drift problem since it does not have filaments and does not require warm-up, as such. However, transistorized equipment is still subject to some drift caused by expansion and contraction of parallel lines and coaxial tanks with variations in temperature.

The magnitude of the drift problem in uhf equipment, compared to vhf, will be understood when the problem is related to a specific circuit such as the local oscillator of a vhf/uhf tv receiver. A uhf local oscillator must operate at several times the frequency of a vhf oscillator, but the i-f passband is the same for both. For example, assume that a vhf local oscillator operates at 100 MHz, while the uhf oscillator operates at 900 MHz. The i-f passband is 6 MHz wide in either case (for the average vhf/uhf tv receiver). Drift is usually expressed as a percentage of the operating frequency. A vhf oscillator (100 MHz) with a 1% drift would have a total drift of 1 MHz, still well within the i-f passband. However, a uhf oscillator (900 MHz) with a 1% drift would have a total drift of 9 MHz. This would be half again as large as the 6-MHz band. For these reasons, the local oscillators of most uhf tv converters and tuners are provided with some form of temperature compensation,

usually negative temperature-coefficient capacitors. These capacitors decrease in capacitance as the temperature rises. This offsets the normal tendency of the converter or tuner to drift lower in frequency with a temperature increase. As the temperature rises, the parallel lines or coaxial tanks expand, raising the inductance and lowering the resonant frequency. The decrease in capacitance of the negative temperature-coefficient capacitors tends to offset this condition, since it raises the resonant frequency. In any servicing operation involving the replacement of capacitors in uhf oscillator circuits, great care must be taken to replace critical capacitors with ones having the correct temperature coefficient.

8

Transmitter Circuits for UHF

Uhf transmitters are basically the same as transmitters for lower-frequency operation. The only significant difference between them is in the final amplifier stages. Most present-day uhf transmitters use crystal-controlled oscillators followed by a series of frequency multipliers similar to those of vhf or other lower-frequency transmitters. Only the final amplifier stage is a true uhf circuit, using parallel-line or coaxial-tank circuits. Signal generators, grid-dip meters, and similar units of test equipment are about the only units that use a uhf oscillator working "straight through" to the final output. Of course, there are exceptions which will be discussed later.

If you are now working with vhf or lower-frequency transmitter equipment, you will have no great problem switching over to uhf. However, there are just enough differences to cause trouble if they are ignored. These differences are discussed in the following sections.

BASIC UHF TRANSMITTER CIRCUIT

To obtain a high degree of frequency stability, any transmitter must be crystal controlled. Since the crystal-controlled oscillator operates at a relatively low frequency, it is necessary for a uhf transmitter to employ several frequency-multiplier stages to obtain the desired operating frequency. Fig. 8-1 shows the block diagram of a typical uhf communications transmitter using such an arrangement. Here, the desired operating frequency is 468 MHz and the oscillator operates at 13 MHz. The 13-MHz output signal of the oscillator is passed through a phase modulator to a chain of four frequency-multiplier stages. The frequency is progressively multiplied to 26,

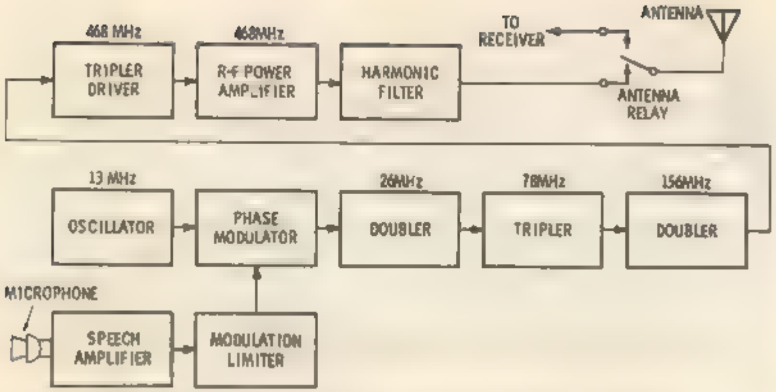


Fig. 8-1. Block diagram of a typical uhf transmitter.

78, 156, and 468 MHz. No frequency multiplication occurs in the r-f power-amplifier stage. As discussed in later sections, both the input and output tank circuits of this final stage use parallel-line or coaxial-tank circuits, rather than the conventional coil-capacitor tank circuits.

CRYSTAL OSCILLATORS FOR UHF

Uhf crystals are not practical. The operating frequency of a quartz crystal is determined by its thickness. The thinner the crystal, the higher the frequency. At ultrahigh frequencies, a quartz crystal would be so thin that it could easily be cracked or damaged. Therefore, uhf crystal oscillators operate in the high-frequency range (3 to 30 MHz). A popular crystal-oscillator circuit is shown in Fig. 8-2. The oscillator frequency is determined by the crystal and its "rubbering" capacitor (C1), which allows adjustment of the frequency over a very narrow

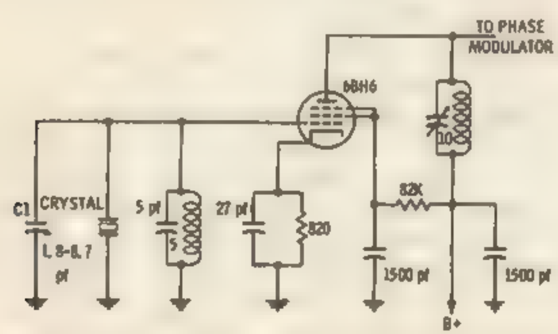


Fig. 8-2. A typical crystal-controlled uhf oscillator.

range. Most uhf crystals are housed in a thermostat-controlled oven; this is required for adequate frequency stability. The oven temperature is maintained above the ambient temperature so that off-frequency operation will not result during hot weather. The reason for this high degree of frequency control in uhf oscillators is the multiplication factor. A typical 13-MHz oscillator output is multiplied 36 times to produce a 468-MHz final-amplifier signal. Any error in oscillator frequency is also multiplied 36 times. For example, a 1-kHz error at the oscillator will produce a 36-kHz error at the output.

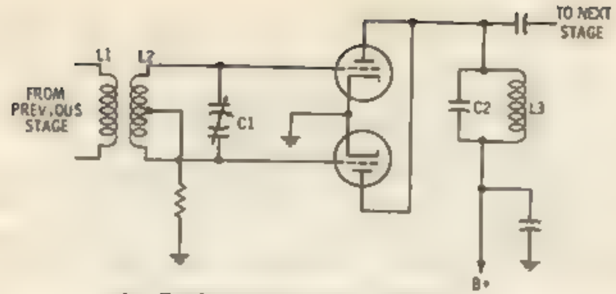
FREQUENCY-MULTIPLIER CIRCUITS

The frequency-multiplier circuits for uhf are basically the same as those for lower frequencies. However, several unusual circuits have been developed especially for uhf, because of the high multiplication factor required.

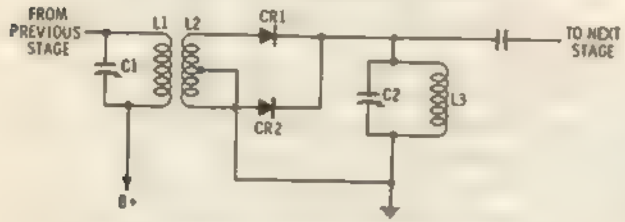
Fig. 8-3 shows three types of frequency multipliers. The push-pull frequency doubler (Fig. 8-3A) has its input circuit L2-C1 tuned to the frequency of the previous stage. Its output circuit C2-L3 is tuned to the second harmonic of the input signal. Another doubler circuit, shown in Fig. 8-3B, employs a pair of semiconductor diodes instead of vacuum tubes. It is simply a full-wave rectifier. When CR1 is driven positive, it conducts and CR2 does not conduct. When the input signal reverses polarity, CR1 stops conducting and CR2 conducts. Consequently, current flows through C2-L3 during both half-cycles of the input signal. The resulting signal across C2-L3 is at twice the input-signal frequency.

Many frequency multipliers used in uhf work employ a class-C amplifier, as shown in Fig. 8-3C. Here, the input signal to which L1-C1 is tuned is fed to the grid. Since the cathode is grounded and there is no fixed bias, a positive signal at the grid causes grid current to flow and the plate current to increase. Capacitor C3 is charged. When the grid "sees" a negative signal, the charge across C3 and the signal voltages are in series-adding. This makes the grid very negative, thus causing the plate current to stop. Only positive signals at the grid cause plate current to flow. As a result, the output waveform is distorted and, consequently, rich in harmonics. The desired harmonic is selected by tuning the C2-L2 combination. This kind of circuit is generally used to double, triple, or quadruple the input frequency.

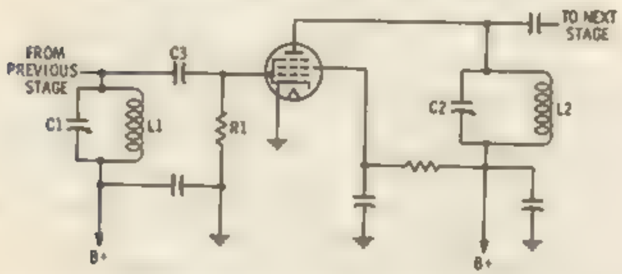
One of the serious problems in uhf frequency multiplication is the elimination of unwanted harmonics that may be present



(*A*) *Push-pull frequency doubler.*



(*B*) *Frequency doubler using diodes.*



(*C*) *Frequency multiplier using a Class-C amplifier.*

Fig. 8-3. Typical frequency-multiplier circuits.

simultaneously with the desired harmonics. For example, if a particular multiplier is to act as a doubler and produces desired harmonics at twice the input frequency, there may also be undesired harmonics at three times the frequency, four times the frequency, etc. This can be overcome by means of a double-tuned circuit which acts like a filter. An example of this is shown in Fig. 8-4. Here, the circuit is a frequency doubler used in a General Electric uhf f-m communications transmitter. The input signal from the oscillator is fed to the grid through the phase modulator. This signal is at some frequency between 12.5 and 13.5 MHz, depending on the desired transmitter operating frequency. Through a series of these multipli-

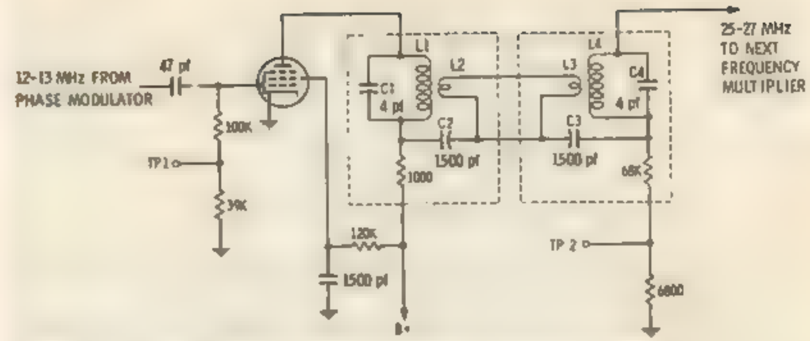
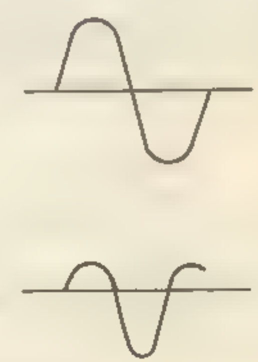


Fig. 8-4. Frequency doubler with tuned filter.

cation circuits, the oscillator signal is multiplied 36 times to obtain the desired output frequency of about 468 MHz. Operation of the circuit is straight-forward (plate load C1-L1 is tuned to twice the input-signal frequency, and from this point the signal is link-coupled to L4-C4, also tuned to twice the input frequency). However, because it is a *two-stage* tuned circuit, it acts as a filter, offering greater rejection of unwanted harmonics and spurious signals than a conventional single-tuned circuit.

Any circuit or device that is rich in harmonics can be used as a frequency multiplier. One such device is a varactor diode. Varactor diodes, known by various names such as *Varicap*, etc., possess unusual characteristics. They are essentially capacitors whose value can be changed by varying the voltage

Fig. 8-6. Effect of a varactor on a sine wave.



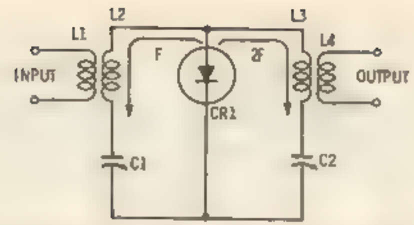


Fig. 8-6. Basic varactor doubler circuit.

applied across them. As a result, they are very rich in harmonics and can be used as multipliers.

Fig. 8-5 shows the effect of a varactor diode on a sine wave. The waveform in Fig. 8-5A is the input signal, and the waveform in Fig. 8-5B is the output signal. The waveforms merely represent the concept and are actually much more complex.

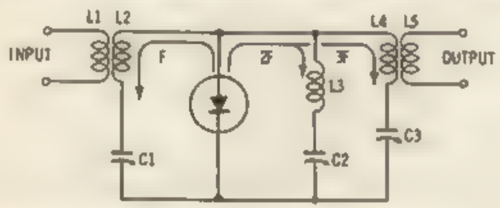


Fig. 8-7. Basic varactor tripler circuit.

In the basic varactor doubler circuit shown in Fig. 8-6, L2-C1 is tuned to the frequency of the input signal applied to L1. The output circuit, L3-C2, is tuned to the second harmonic of the input signal. The signal induced into L4 is at twice the input-signal frequency.

Fig. 8-7 shows a basic varactor tripler circuit. Here, C1 and L2 are tuned to the input frequency, L3 and C2 to the second harmonic, and L4 and C3 to the third harmonic.

A practical frequency tripler employing a varactor diode is

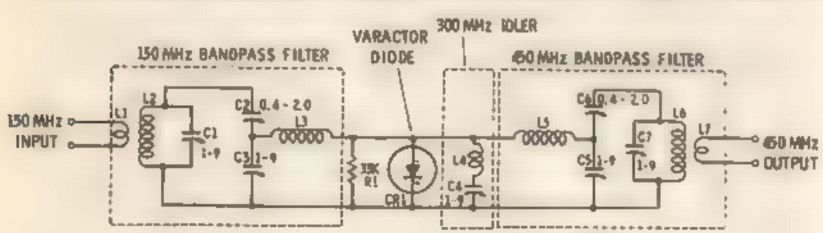


Fig. 8-8. Practical tripler circuit using a varactor.

shown schematically in Fig. 8-8. With a 150-MHz signal at the input, the output is at 450 MHz. This frequency multiplier is simple and requires no power supply. A link-fed, 150-MHz, double-tuned bandpass filter is formed by L2-C1 and L3-C3, with C2 serving as the coupling between the two sections of the filter. The signal is shunted by varactor diode CR1 which, because of its nonlinearity, causes harmonics of the 150-MHz signal to be generated. Self-bias for the varactor is developed across R1. For maximum efficiency, second-harmonic current must flow. This flow is accomplished in series-resonant circuit L4-C4, which is tuned to 300 MHz and shunted across the varactor. The double-tuned bandpass filter L5-C5, L6-C7, coupled by C6, is tuned to 450 MHz.

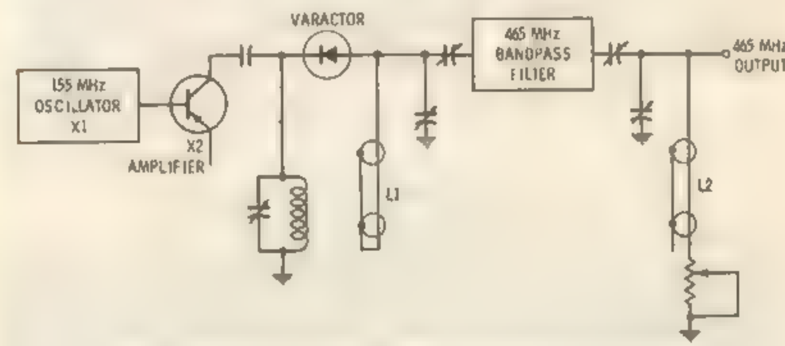


Fig. 8-9. Experimental solid-state uhf transmitter.

Another frequency-multiplier circuit for uhf using a varactor is shown in Fig. 8-9. This is an experimental uhf transmitter using all solid-state components. The signal is generated by a vhf crystal-controlled oscillator using transistor X1. The signal is amplified at the same frequency by X2 and fed through a varactor diode to a 465-MHz tuned circuit L1 consisting of a 0.1 × 465-MHz shorted section. The resulting uhf signal is fed through a bandpass filter to a second shorted section.

MODULATION AND AUDIO CIRCUITS FOR UHF TRANSMITTERS

The modulation and audio circuits for uhf transmitters are identical to those of lower-frequency equipment. Therefore, they will not be discussed here. However, one point to remember is that in frequency modulation, the basic oscillator frequency is varied by the modulator. In uhf, the basic oscillator

frequency is also multiplied many times. Therefore, the amount of deviation is also multiplied. For example, if the oscillator is varied 1000 Hz and the multiplication factor is 36, the final r-f stage is varied 36 kHz.

POWER-AMPLIFIER CIRCUITS FOR UHF

The final power-amplifier stages of uhf transmitters are similar to those of lower-frequency equipment, except for the use of parallel lines or coaxial lines for tank circuits. These

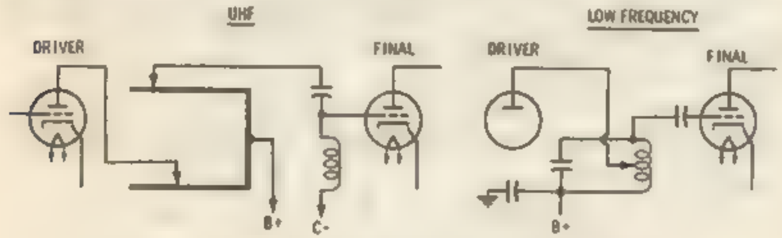


Fig. 8-10. Typical capacitive interstage coupling.

lines operate as resonant circuits, usually shorted quarter waves, and can be tuned by a movable shorting bar or by a variable capacitance across the lines. The final stage of most uhf transmitters does not (usually) provide frequency multiplication. Therefore, the driver stage just ahead of the final must have a uhf type of tank circuit. This means that special methods must be used for interstage coupling of uhf circuits. There are three basic methods of coupling: (1) capacitive, (2) link, and (3) direct.

Fig. 8-10 shows both the low-frequency and uhf versions of capacitive coupling. A voltage step-up is obtained from plate to grid since the final-stage grid is tapped into the shorted quarter-wave line at a higher impedance point than the driver plate. Bias for the final stage is supplied through an r-f choke, while the grids are isolated from B+ by a capacitor.

Fig. 8-11 shows the low-frequency and uhf versions of link coupling. One of the advantages of link coupling is that a minimum of power is lost, since both the input and output occur at low-impedance points on the line. Also, no capacitance is required between the stages. In lower-frequency circuits, link coupling is often used where the driver and final stages are widely separated. Link coupling is not too practical at ultrahigh frequencies, however, because the long leads between the link offer a high inductance.

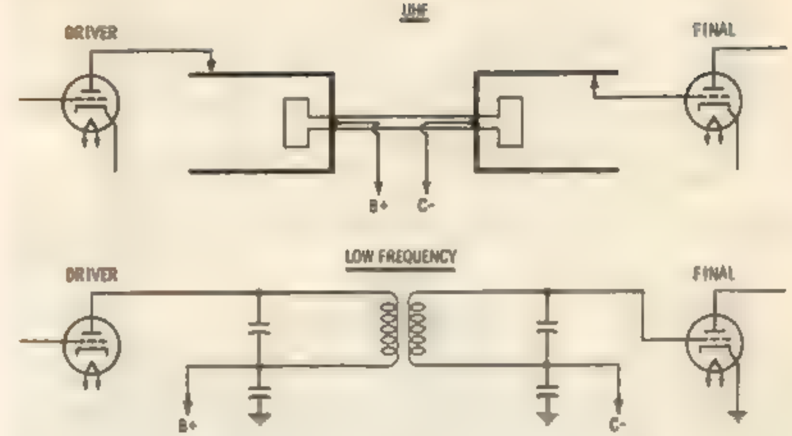


Fig. 8-11. Typical link interstage coupling.

Fig. 8-12 shows the low-frequency and uhf versions of direct coupling. This circuit is often used where the final stage requires a low impedance to the grid, while the driver stage requires a high impedance at the plate. As shown, the plate is tapped in through a B+ isolating capacitor to the high-impedance end of the shorted quarter-wave line. The final grid is tapped directly into the line near the low-impedance or shorted end. This grid receives its bias directly through the line.

Fig. 8-13 shows the low-frequency and uhf versions of how a single-ended driver can be coupled to a push-pull final. This is a combination of direct and capacitive coupling. The driver plate is coupled to the high-impedance end of the line, while

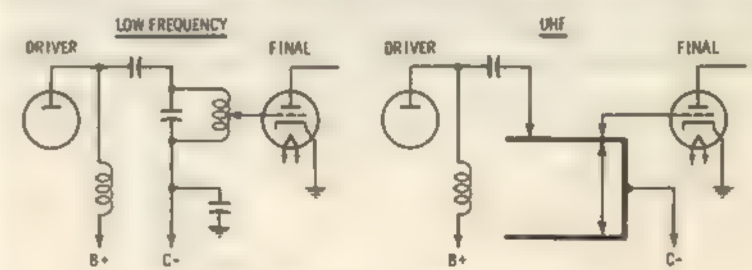


Fig. 8-12. Typical direct interstage coupling.

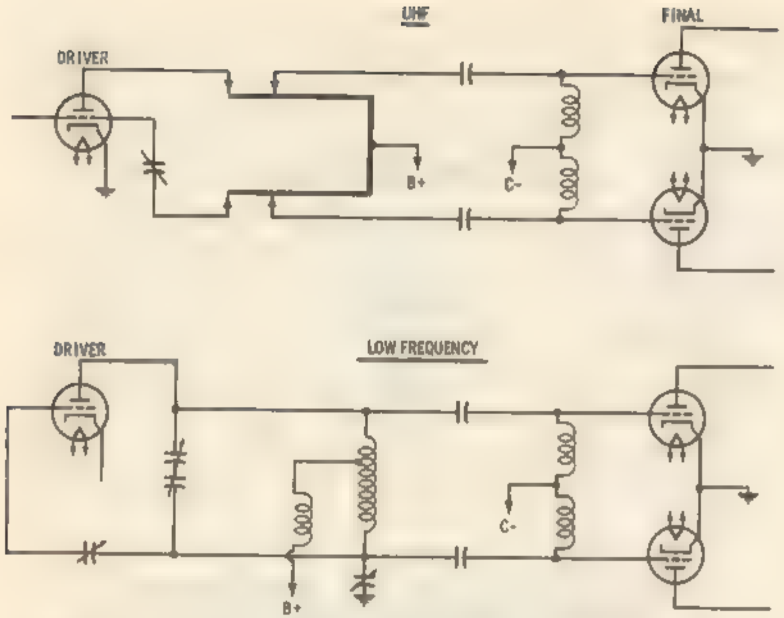


Fig. 8-13. Coupling a single-ended driver to a push-pull final.

the driver grid is coupled to the opposite line through a neutralizing capacitor. The 180-degree phase shift between the lines cancels the plate-grid voltage feedback and prevents undesired oscillation. The grids of the final stage are connected to a low-impedance point on the line through isolating capacitors. The B+ is applied to the center of the shorted line.

Special methods must also be used to couple the final stage to the antenna. Both link or inductive coupling and direct coupling can be used. With inductive coupling (Fig. 8-14), a pickup loop is placed within the transmission line's magnetic field and is positioned along the line at a point where the impedance matches that of the antenna. With direct coupling (Fig. 8-15), the antenna is tapped directly to the transmission line through an isolating capacitor. The antenna impedance is matched by positioning the taps along the line. Fig. 8-15A shows the arrangement in which the feed line to the antenna is unbalanced,

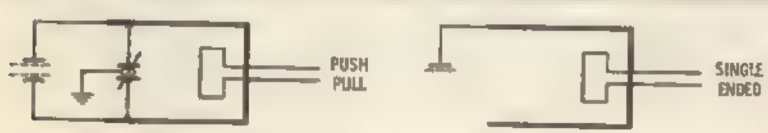


Fig. 8-14. Link coupling a uhf amplifier to an antenna.

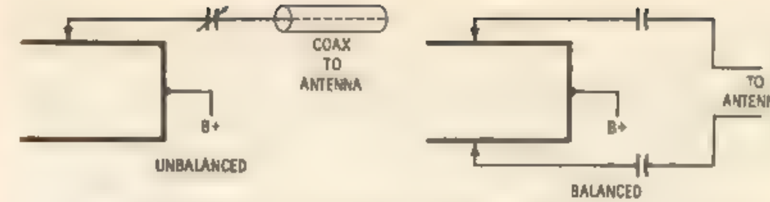


Fig. 8-15. Direct coupling a uhf amplifier to an antenna.

such as a coaxial cable. Fig. 8-15B shows a balanced feed-line configuration.

OUTPUT FILTERS

Because of the frequency multiplication required for most uhf transmitters, many undesired harmonics are often present at the output. For this reason, uhf transmitters are usually provided with harmonic filters between the final output and the antenna. At the low end of the uhf band, these filters can use coils and low-value capacitors. As the operating frequency

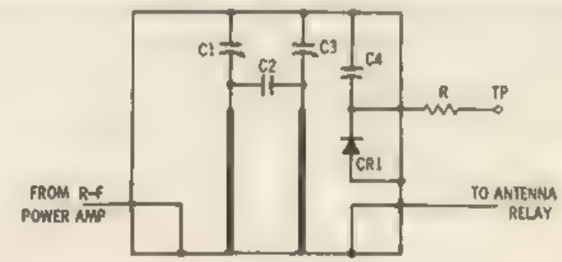


Fig. 8-16. An r-f filter for a uhf transmitter.

increases, the filters use parallel-line or coaxial tanks. Such an arrangement is shown in Fig. 8-16. This is a double-tuned tank with a built-in test point. R-f energy within the tank is picked up and rectified by CR1. The d-c output is available at TP1, permitting the tank to be tuned to the desired frequency.

9

Receiver Circuits for UHF

Like uhf transmitters, uhf receivers are similar to those used at lower frequencies. Unlike transmitters, it is the front end or input of the uhf receiver that makes it quite different from lower-frequency units. This front end includes the r-f stage (if any), the mixer or first detector, and the local oscillator. The remaining stages (i-f amplifier, second detector, audio, third detector, etc.) are the same as for low-frequency units. In fact, in uhf tv, the same receiver is used for both uhf and vhf, the only difference being in the tuner circuit. Separate tuners are used for uhf and vhf. In each case, the tuners contain r-f, mixer, and local-oscillator stages. Actually, the basic front-end circuits of uhf receivers are conventional, except for the use of parallel lines and coaxial lines for tuning or tank circuits. Each stage of the front-end circuit is discussed in the following sections.

RADIO-FREQUENCY STAGES

There are two schools of thought for uhf receiver radio-frequency stages. Where the transmitted signal is relatively strong, such as with tv, no amplification is used with the r-f stages. On the other hand, in applications such as mobile communications where transmitter power is relatively low, the r-f signals require some boost. The same is true of uhf tv in fringe areas where the signal is weak. However, the r-f amplification is usually supplied by an external booster or amplifier, and not in the receiver itself. Most tv receivers, uhf and vhf, are designed for medium to strong signal areas.

Where no signal amplification is required, the r-f stage consists of a simple tuned circuit. In practically all cases this is a

coaxial tank or a parallel line. The use of an r-f stage without amplification eliminates two basic problems. One of them is tube noise. Any type of tube will produce some noise. Since the r-f tube is at the beginning of all amplification in the re-

Fig. 9-1. Typical uhf grounded-grid r-f amplifier.

ceiver, any noise will also be amplified to the full extent. A triode will produce the least noise. However, a triode requires neutralization when used as an amplifier. Without neutralization, it will tend to oscillate. This is the second problem.

There are two basic r-f amplifier circuits: (1) the grounded cathode and (2) the grounded grid. It is possible to use two tubes in cascade to provide maximum r-f amplification. It is also possible to use a tube in the r-f stage, such as a cathode follower, without amplification. However, this arrangement is used primarily as an impedance-matching system.

Fig. 9-1 shows a typical grounded-grid r-f amplifier. The cathode is connected to one end of the input tank circuit, the plate is connected to one end of the output tank circuit. The

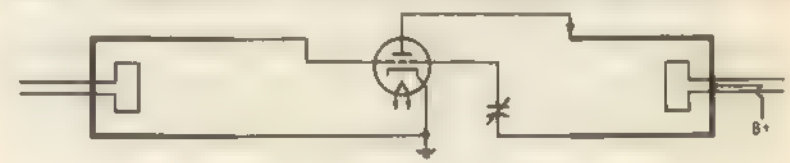


Fig. 9-2. Typical uhf grounded-cathode r-f amplifier.

grid is at ground. When the cathode swings negative in relation to the grid, current increases and amplification takes place. Although a grounded-grid amplifier has less voltage gain than the conventional grounded cathode, a low-noise triode can be used without neutralization.

Fig. 9-2 shows a typical grounded-cathode r-f amplifier. Except for the parallel-line input and output tanks, this circuit operates like any r-f amplifier. Noise will be minimum with a triode. However, the triode must be neutralized.

Fig. 9-3 shows a typical cathode follower used in an r-f stage. The input is applied to the grid, the output is taken from the

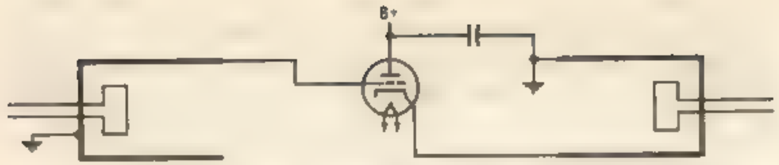


Fig. 9-3. Typical cathode follower for uhf input.

cathode, and the plate is connected to B+. This provides a low impedance at the output, and a high impedance at the input. No neutralization is required, and no gain is available.

Fig. 9-4 is a cathode-coupled cascade amplifier used where extra amplification is needed, and where both the input and output must be at a high impedance. The two stages are coupled by a common-cathode resistor. Any variation in current

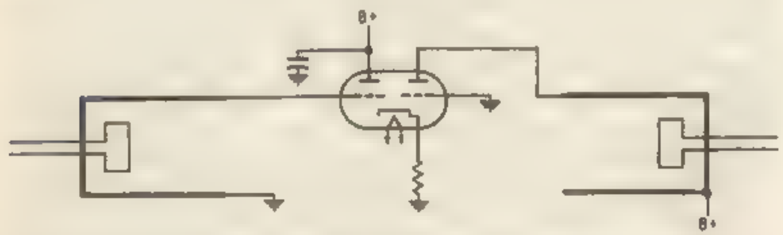


Fig. 9-4. Typical uhf cathode-coupled cascade amplifier.

through the input-stage half of the tube causes a change in cathode voltage. This, in turn, causes a current change in the second, or output half, of the tube. Amplification is obtained in both halves. The first, or input half, operates as a grounded-

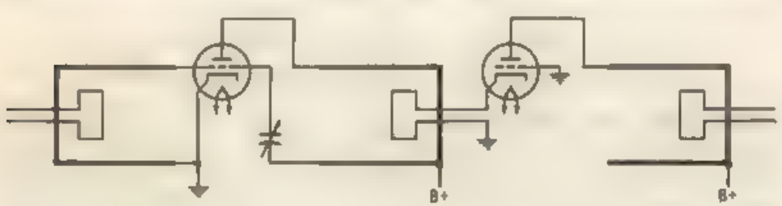


Fig. 9-5. A driven cascade amplifier for uhf.

cathode amplifier, and the second half operates as a grounded-grid amplifier.

Fig. 9-5 is a similar circuit but uses two separate tubes instead of cathode coupling. The input stage is a grounded cath-

ode, and the output, or driven, stage is a grounded grid. This circuit requires three tuned tanks instead of two.

Fig. 9-6 also requires three tuned tank circuits, but both stages are grounded grid. This provides less amplification, but eliminates the need for neutralization.

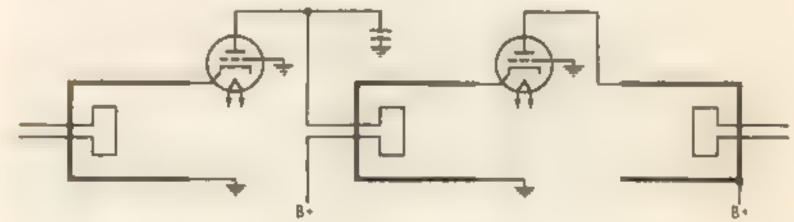


Fig. 9-6. A driven cascade amplifier for uhf using two grounded-grid stages.

Fig. 9-7 uses a dual triode to provide a grounded-cathode input and a grounded-grid output by direct coupling. As shown, the cathode of the first section is connected to ground to complete the d-c circuit. The plate of this section is connected directly to the cathode of the next stage. The grid of the second section is at r-f ground through the capacitor. Plate current

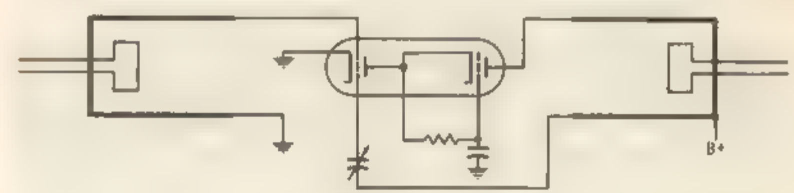


Fig. 9-7. A driven cascade amplifier for uhf using a dual triode.

flows through both sections, from the cathode of the first section to the plate of the second section. Output is taken from the second plate, and bias is developed across the cathode-grid resistor.

MIXER STAGES

The mixer stage of a uhf receiver (also known as the first detector or converter) generally uses a crystal diode rather

than a vacuum tube. The crystal diode has many advantages: the most obvious is that it requires no heater or other power. It is also more rugged, has less capacitance and inductance to introduce into the circuit (an important point for uhf work), and has low contact resistance. Although both silicon and germanium diodes could be used, germanium diodes are the more

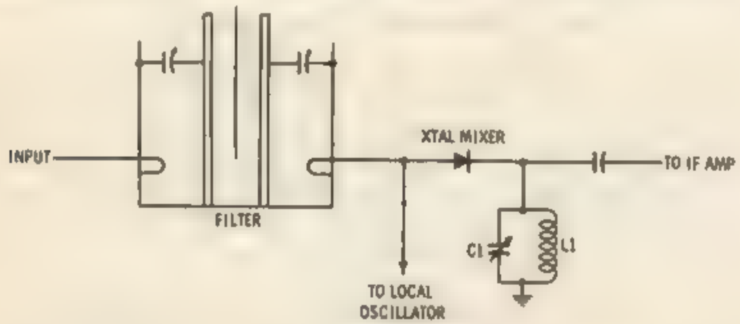


Fig. 9-8. A typical uhf receiver input stage using a crystal-diode mixer.

popular for uhf. Fig. 9-8 is a typical uhf receiver input stage using a tuned r-f input (without amplification) and a crystal mixer. The output tank circuit of L1 and C1 is tuned to the i-f beat resulting from the heterodyning of the received signal with the local-oscillator signal. The input is double tuned to the antenna frequency by the coaxial tank.

In a few cases, a special-purpose uhf tube is used as the mixer. The mixer circuit shown in Fig. 9-9, for example, uses a 6AM4 triode tube in a grounded-grid configuration. The input circuit is tuned to the frequency of the desired incoming signal by a double, resonant-line filter. Fine-frequency adjust-

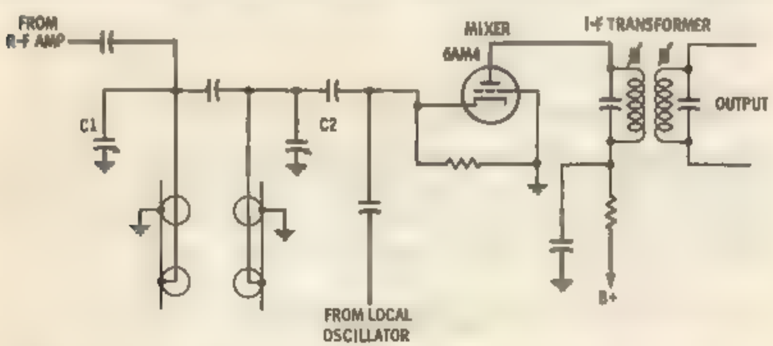


Fig. 9-9. A uhf mixer stage using a 6AM4 tube in a grounded-grid configuration.

ment is accomplished with C1 and C2. The i-f transformer is tuned to the i-f beat produced by the heterodyning of the received signal with the locally generated signal.

LOCAL-OSCILLATOR STAGES

Where a variable-frequency local oscillator must be used, such as with a uhf tv tuner or converter, the basic oscillator circuit is operated at the ultrahigh frequency. Where the oscillator can be at a fixed frequency (or at several fixed frequencies, such as with a communications receiver operating on various channels), the basic oscillator circuit is crystal controlled, and the ultrahigh-frequency signals are obtained by multiplication.

VARIABLE-FREQUENCY LOCAL OSCILLATORS

The most common use for uhf variable-frequency local oscillators is in uhf tv. In most cases, these oscillators use the ultraaudion circuit described in Chapter 7. This circuit is used in both uhf tv converters and tuners as the local oscillator. The following sections describe operation of a typical uhf tv tuner and converter.

TYPICAL UHF TV TUNER OPERATION

Practically all uhf tv tuners currently being manufactured use coaxial tanks or parallel-line tanks, with the trend going strongly in favor of the coaxial tank. The most popular version is the coaxial tank with capacitor end tuning. One of the reasons for this type of tuning is that parallel-line tanks depend on sliders or wipers for tuning. Like any moving contact, such sliders can create service problems when they become worn, dirty, or loose and make poor electrical contact. Another reason is that the capacitor end-tuned units can usually be made more compact, since the outer tuner shield also forms the outer conductor of the coaxial tank circuit.

A typical continuously tuned, single-conversion tuner is pictured in Fig. 9-10. The schematic for this tuner appears in Fig. 9-11. The tuner converts uhf signals into intermediate-frequency signals of 40 to 46 MHz. The local oscillator uses a 6AF4A triode, and the mixer uses a 1N82A silicon diode or crystal. This uhf tuner duplicates the conversion normally accomplished by the uhf tuner, producing a video carrier of 45.75 MHz together with a sound carrier at 41.25 MHz. This is ac-

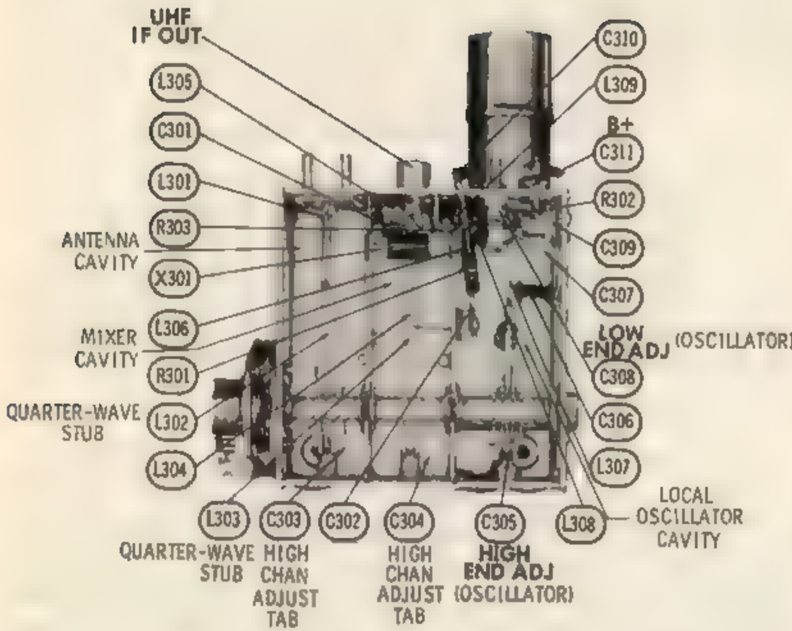


Fig. 9-10. Capacitor end-tuned uhf tv tuner.

complished by operating local oscillator V301 at 45.75 MHz above the incoming uhf video carrier.

Input Tanks

The uhf input (balanced for a 300-ohm line) is applied through a separate set of terminals to antenna coil L301. This coil is located in the antenna coaxial cavity and provides inductive coupling to it. The antenna cavity is coupled to the mixer cavity (which also functions as a second antenna cavity) through a window in the partition between the two. Both cavities are tuned to the same approximate frequency by the ganged variable capacitors driven by the channel-selector knob. The combination of two antenna cavities acts as a preselector to provide better matching between the antenna and the mixer crystal. It also increases the rejection of image frequencies.

Cavity Tuning and Trimming

Each of these two cavities is a separate coaxial tank and contains a shorted quarter-wave stub. The variable tuning capacitors change the capacitance between the open end of the stub and ground. When the capacitors are fully meshed (maxi-

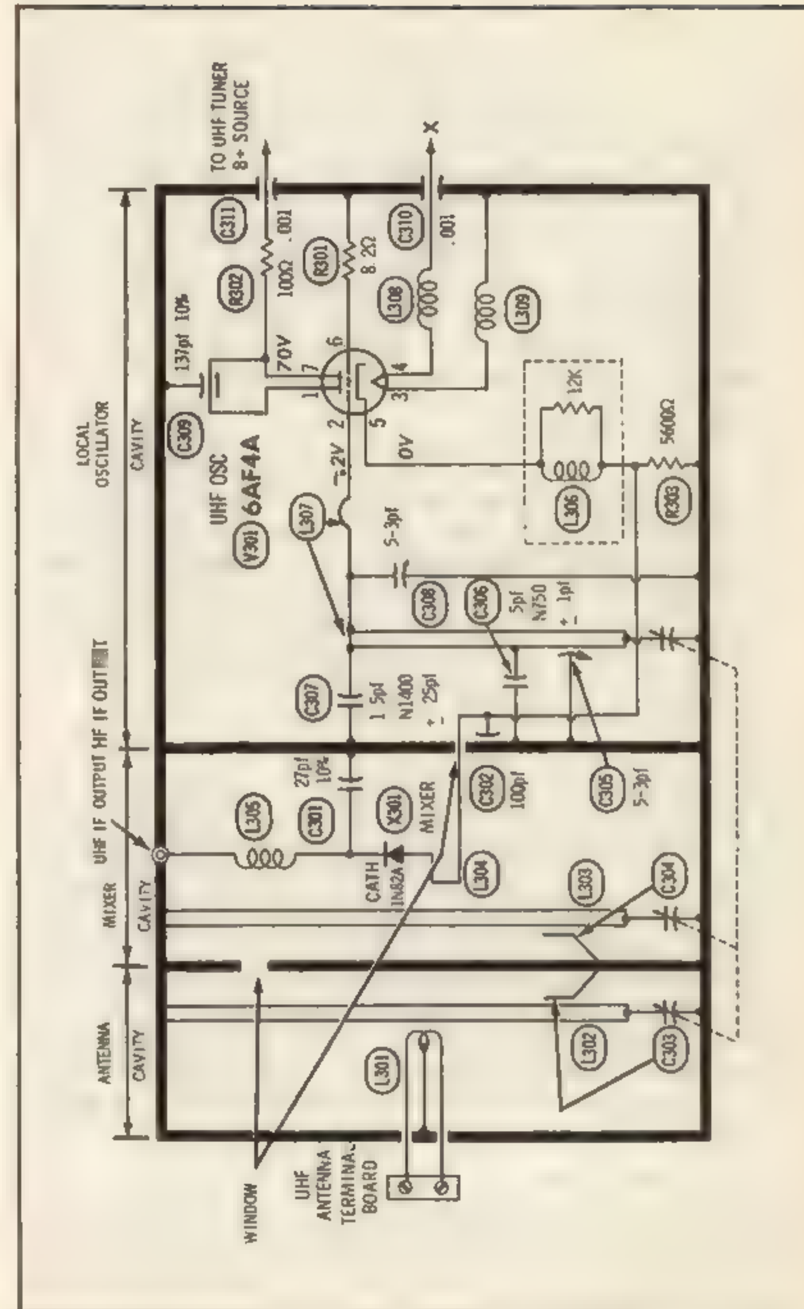


Fig. 9-11. Schematic for the tuner in Fig. 9-10.

mum capacitance), the tank is tuned to the low end of the band. The variable capacitors are designed to provide a straight-line relationship between the tuner and the uhf channel dial.

No provision is made for trimming either of the cavities at the low end of the band. However, the cavities can be trimmed at the high end by means of metal tabs (C303 and C304). Bending these high-frequency adjustment tabs varies the capacitance between the end of the stub and ground, just as does tuning of the variable capacitors. The cavities are tracked across the band by means of slits in the outer plates of the variable capacitors. The outer plates can be "knifed" (bent by inserting a knife in the slots) to provide maximum signal transfer from both cavities across the uhf band.

Matching Input Impedance

The tuner is matched to a 300-ohm antenna lead-in by positioning coil L301 along the quarter-wave stub in the antenna cavity. Like all shorted quarter-wave lines, the impedance is zero at the shorted end and maximum at the open (or capacitor-tuned) end. If coil L301 is replaced for any reason, its replacement must be returned to the exact same position. Otherwise, there will be an impedance mismatch between the tuner and antenna, resulting in signal loss. Also, if the coil is moved during servicing, a mismatch will result.

Mixer Cavity

The r-f signals in the antenna cavity are passed to the mixer cavity through a window in the separating partition. These signals are picked up by the wire loop (L304) connected to the end of the mixer crystal X301. This loop passes through a window in the partition between the mixer and local-oscillator cavities. R-f signals in the local-oscillator cavity are also picked up by the mixer loop and are combined with the antenna signals to produce sum and difference frequencies in mixer crystal X301 Coil L305 and capacitor C301 form a low-pass filter which shunts the sum signals to ground and passes the difference (i-f) signals to the receiver circuits through a shielded coaxial cable.

Local-Oscillator Cavity

The local oscillator is the ultra-audion circuit discussed in Chapter 7. The plate of V301 is capacitively coupled through C309 to the tuner shield that forms the outer conductor of the coaxial tank or cavity. The grid is coupled to the inner conductor or stub. Unlike the antenna and mixer stubs, the local-

oscillator stub is one-half wave long, and it is not shorted at either end. Both a shorted quarter-wave and an open half-wave stub act as parallel-resonant circuits.

One end of the half-wave stub is coupled to the outer conductor through the ganged variable capacitor. The opposite, or grid end, of the stub is coupled to ground through C308. When the capacitors are fully meshed (maximum capacity), the oscillator frequency is at its lowest. The ganged variable capacitor changes the oscillator frequency at the same time it tunes the antenna and mixer cavities. Variable capacitor C308, which adjusts the local oscillator to the desired frequency (40 to 46 MHz above the incoming uhf signals), is the main alignment point. As shown in Fig. 9-10, capacitor C308 can be adjusted from the outside of the tuner without removing the shield. Since the shield forms a portion of the outer conductor for all three tanks, the tank frequency is changed when the shield is removed and replaced.

The local-oscillator cavity can also be trimmed at the high end of the band (channel 60 and up) by means of high-frequency adjustment screw C305. However, the tuner shields must be removed to adjust the screw, just like the antenna and mixer-cavity adjustment tabs.

Local-Oscillator Modifications

Local oscillator V301 is actually a form of Colpitts oscillator with several modifications. Plate voltage is supplied from the receiver through resistor R302 and feedthrough capacitor C311. Although the plate is 70 volts above d-c ground, capacitor C309 has a very low impedance at radio frequencies, and it effectively shorts the plate to the outer conductor. The grid is connected directly to one end of the inner conductor (half-wave stub). The cathode is just slightly above d-c ground. Because of the impedance developed across inductor-resistor L306, however, the cathode is above r-f ground and serves as a reference point for the Colpitts circuit. The capacitance from cathode to ground, together with the grid-plate capacitance, forms the split-capacitance feedback system necessary for oscillation in a Colpitts circuit. Filament voltage for V301 is supplied through capacitor C310 and chokes L308 and L309.

Local-Oscillator Drift

As discussed in Chapter 7, local-oscillator drift is a problem in uhf equipment, because the local oscillators must operate at such high frequencies in relation to the i-f passband. Usually such drift is the result of temperature variation (warm-up,

room-temperature changes, etc.), so the local oscillator must be temperature compensated. For the tuner in Fig. 9-11, this is accomplished by capacitors C306 and C307, which are fixed, precision capacitors with negative temperature coefficients. These capacitors are connected between the inner conductor and outer conductor of the oscillator cavity, and they serve to vary the capacitance and consequently shift the frequency in opposition to the frequency drift caused by the temperature changes. Normally, an increase in temperature will decrease the oscillator frequency. With the addition of negative temperature-coefficient capacitors, temperature increases lower the capacitance. This, in turn, increases the oscillator frequency.

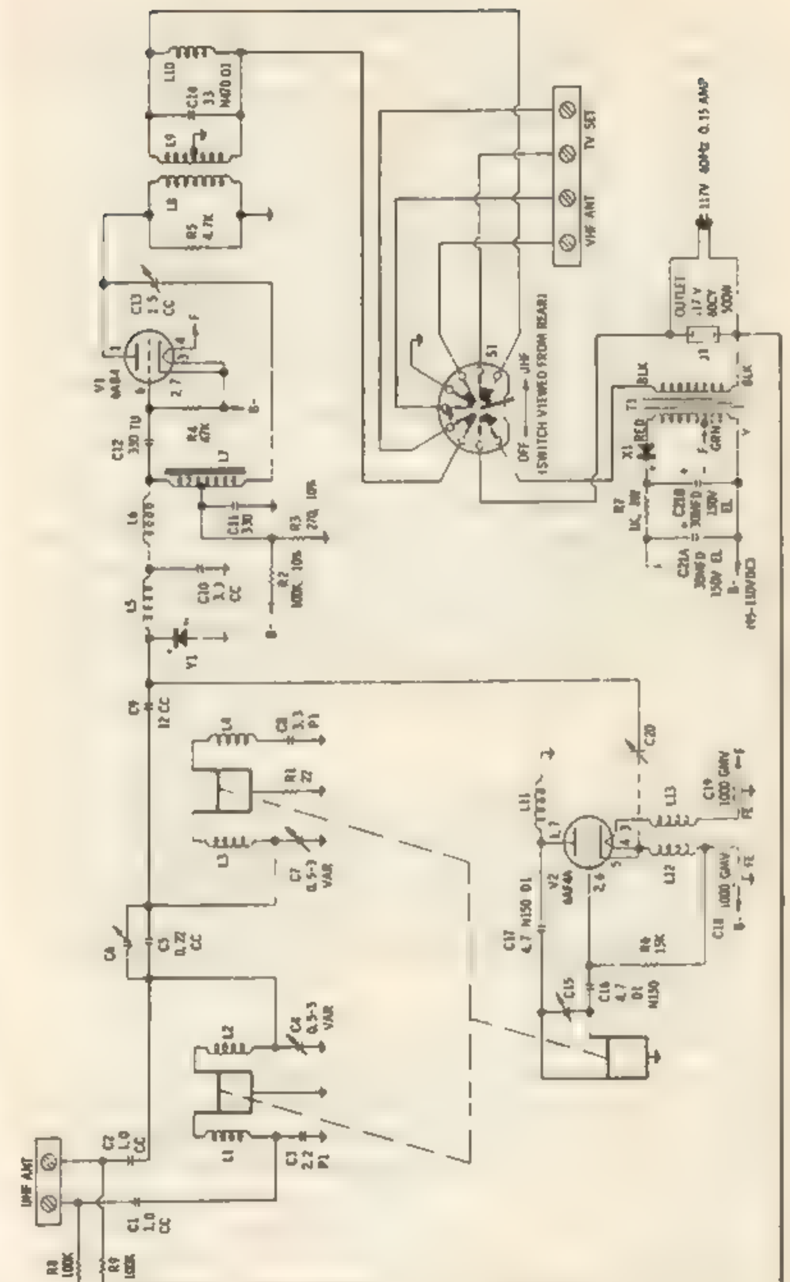
Replacement of Temperature-Compensating Capacitors

Positioning of the temperature-compensating capacitors is very critical. When the variable capacitors are tuned, the voltage maximum and minimum points move along the line. The temperature-compensating capacitors will be effective at or near voltage maximum points only. Therefore, capacitor C306 is placed at a point where it will be effective when the tuner is operating near the high end of the band. The low end is covered by capacitor C307. However, because C307 is near the grid of V301, it is actually effective across most of the band. Other capacitors may be added during manufacture, if additional temperature compensation is required for a particular tuner. It should be noted that the temperature-compensating capacitors present a problem in servicing tuners. Since they are precision capacitors, exact replacements must be used, both in capacitance value and temperature coefficient. Of equal importance, the capacitors must be returned to the exact location along the line.

TYPICAL UHF TV CONVERTER OPERATION

All-channel converters are the most popular means of converting an existing vhf set for uhf reception. The function of an all-channel converter is to change the signals from any uhf channel (14 to 83) to a specific vhf channel (2 to 13) signal. This signal is then processed through the vhf tuner of the tv set in the normal manner on a channel not used for local stations. Most converters are designed for conversion to vhf channel 5 or 6, although some will convert to channel 3 or 4.

The following sections describe a typical all-channel converter using parallel lines. It should be noted that most converters use parallel lines rather than the capacitor end-tuned



Courtesy Blonder-Tongue Labs., Inc.

Fig. 9-12. Uhf tv converter with parallel-line tuning.

circuits. This is just the opposite of the uhf tuners that are built into a vhf/uhf set. The schematic of Fig. 9-12 is typical of the parallel-line converters that use vacuum tubes. All-solid-state converters are also now in use.

In normal operation, both the uhf and vhf antennas are connected to the converter. The output of the converter is connected to the normal vhf input of the receiver. When vhf reception is desired, the converter selector switch is set to OFF. In this position the tv set is connected to the vhf antenna, and power is removed from the converter circuits. When uhf reception is desired, the converter selector switch is set to UHF, and the vhf tuner is set to the converter output vhf channel. In this position, the tv set is connected to the converter output, the vhf antenna is grounded, and power is applied to the converter circuits.

This type of converter has four stages: (1) a tuned r-f stage that receives its input from the uhf antenna, (2) a tuned mixer stage that uses a crystal for the mixing process, (3) a local-oscillator stage that is tuned below the uhf channel frequency to provide a mixer frequency that is the converter output vhf channel, and (4) a vhf amplifier stage. The local-oscillator output is below the uhf input to prevent inversion of the signals. The local oscillator is a 6AF4A triode, and mixer Y1 is a 1N82A silicon crystal. The output amplifier is a 6AB4 triode.

Input Circuit

The uhf input is applied through the uhf antenna terminals to a balancing network that matches the 300-ohm antenna lead-in to the antenna parallel lines. The output from the balancing network is capacitively coupled to the antenna parallel lines, which are then capacitively coupled to the mixer parallel lines (L3, L4) through fixed capacitor C5 and coupling adjustment capacitor C6.

Parallel-Line Tuning

Both parallel lines are tuned to approximately the same frequency by shorting bars which are driven along the lines when the converter dial is rotated. The drive is accomplished through a dial cord. Both parallel lines are trimmed by means of variable capacitors C4 and C7. The lines are tracked by means of inductances L2 and L3, which are adjustable.

Mixer Stage

The r-f signals from the mixer parallel lines are capacitively coupled through C9 to mixer crystal Y1. This crystal also re-

ceives signals from the local oscillator through capacitor C20. These signals are combined to produce sum and difference frequencies. Coil L5 and capacitor C11 form a low-pass filter which shunts the sum (uhf) signals to ground and passes the difference (vhf) signals to the vhf tuner.

Local Oscillator

The local oscillator is the modified Colpitts or ultra-audion discussed in Chapter 7. The plate of the oscillator is capacitively coupled to one parallel line through C17. The grid is coupled to the other line through capacitor C16. Both capacitors C16 and C17 have negative temperature coefficients to prevent drift. The shorting bars across the three sets of parallel lines are coupled to the converter dial. This provides tuning across the uhf band. Variable capacitor C15, across a set of parallel lines, tunes the local oscillator to the desired frequency. Adjustment of C15 varies the electrical (but not the physical) spacing between the lines. This changes their resonant frequency. The cathode of V2 is connected to the filament circuit to eliminate filament-to-cathode capacitance. The local-oscillator r-f output is taken at this junction and applied, through variable capacitor C20, to mixer crystal Y1. Adjustment of C20 sets the level of the local-oscillator injection voltage.

Output Stage

The vhf output from the mixer is amplified by V1, which is a triode, to minimize tube noise. The output of V1 is applied to the vhf tuner input through a matching transformer (L8, L9). Part of the amplified output is fed back through adjustable capacitor C13 to stabilize the amplifier stage.

UHF RECEIVER CHARACTERISTIC DEFINITIONS

Most of the definitions for uhf receiver characteristics are the same as for receivers operating at lower frequencies. Such terms as selectivity, bandwidth, adjacent-channel rejection, image rejection, sensitivity, etc., are the same for uhf and lower frequencies. However, the term *noise figure* is unique to uhf and microwave receivers.

Noise Figure

The noise figure of a receiver is defined as the ratio of noise at the output of an actual receiver to the noise at the output of an ideal receiver. This ideal receiver is one that creates no

noise internally, but is otherwise identical to the actual receiver.

At frequencies below about 30 MHz, static and man-made electrical noise are great enough to mask receiver-generated noise. But at higher frequencies, particularly above 450 MHz, where static and man-made noise are often practically absent, the noise figure of a receiver determines the lowest usable signal level.

There are two basic sources of noise: (1) thermal noise and (2) receiver noise.

1. Thermal noise originates mainly at the receiver input, although it may also be generated in the receiver itself. It may also consist of external noise picked up by the antenna.

   An actual antenna or a dummy antenna is a resistance. A voltage is developed across the open-circuit terminals of this resistance because of the random motion of free electrons due to thermal agitation. This voltage is thermal noise that increases as the receiver bandwidth becomes greater. When resistance is connected to a matched load (receiver input), maximum transfer of thermal-noise power takes place. This is the available noise power.
2. Receiver noise is noise generated in the various receiver circuits. The most significant source of noise is the first tube and its input circuit. It is here that both noise and radio signals are usually amplified to a level high enough to make the noise generated in other stages insignificant. However, if the first tube has low gain, noise originating in other circuits can increase the noise level.

The noise figure of a tube is the ratio of the available signal-to-noise ratio at the input to the available signal-to-noise ratio at the output.

Noise Power Ratio

Very low-noise tubes providing high gain are generally used in the first stage to achieve a low noise figure. In a perfect receiver, the ratio of the noise at the output of the receiver to the noise at the output of an ideal receiver would be 1:1. The noise figure would then be 0 db. Since there is no perfect receiver, noise figures vary from 8 to 30 db. If, in a typical receiver, the noise figure is 12 db, for example, the receiver is 16 times noiser than an equivalent ideal receiver.

Another way of expressing the noise figure is to say that it is the ratio of the receiver-generated noise to the thermal noise,

stated in db. If the receiver-generated noise is equal to the thermal noise, the total noise power is the sum of the two. This is 3 db poorer than ideal. Consequently, the noise figure is 3 db. The noise figure is 10 db when the receiver generates 10 times the thermal noise power.

The situation is made worse when a long antenna transmission line is used. The thermal noise at the receiver input is unaffected, but the signal power is lessened by the losses in the transmission line.

Having a receiver with a low noise figure can be more important than having a higher-powered transmitter. Reduction of the receiver noise figure can have the same effect as increasing the transmitter power several times.

10

UHF Test Equipment and Techniques

Most of the test equipment used at lower frequencies can also be used in uhf work. Such equipment includes vom's, oscilloscopes, tube testers, transistor testers, power supplies, frequency meters, r-f power meters, modulation meters, frequency-deviation meters, etc. Since their operation is basically the same for all frequencies, this equipment will not be discussed here. However, there are certain items of test equipment and certain techniques that are unique to uhf and microwave operation. The following sections describe them.

POWER MEASUREMENT

At uhf and microwave frequencies, the current and voltage in a circuit are complex in nature and difficult to evaluate in terms of their ability to do work. Power, on the other hand, is a real quantity that can be measured and easily related to circuit performance. Unlike the voltage and current levels along a transmission line, microwave power remains constant with position of measurement (in a loss-free line). For these reasons, power is one of the basic measurements made at microwave frequencies.

A great many microwave power measurements are well below 10 milliwatts, where signal generators supply test signals for checking receiver, small-signal amplifier, and detector performance. In some cases the power level may be on the order of only a few microwatts, requiring high sensitivity and stability in the measuring equipment.

BOLOMETRIC POWER METERS

Below 10 milliwatts, power is usually measured with bolometers (temperature-sensitive resistive elements) in conjunction with a balanced bridge. The basic bolometer is a thin wire placed within the r-f energy field. Changes in temperature cause a corresponding change in wire resistance. There are two general types of bolometers: (1) thermistors, whose resistance decreases with temperature increases (negative temperature coefficient), and (2) barretters, which have a positive temperature coefficient. The use of thermistors is more prevalent because they are more rugged, both physically and electrically, than barretters. These tiny bolometer elements are mounted in devices that ideally present a perfect impedance match to uhf and microwave transmission lines, either

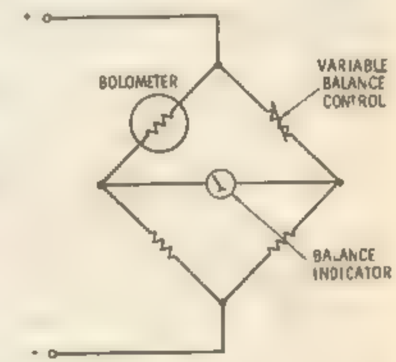


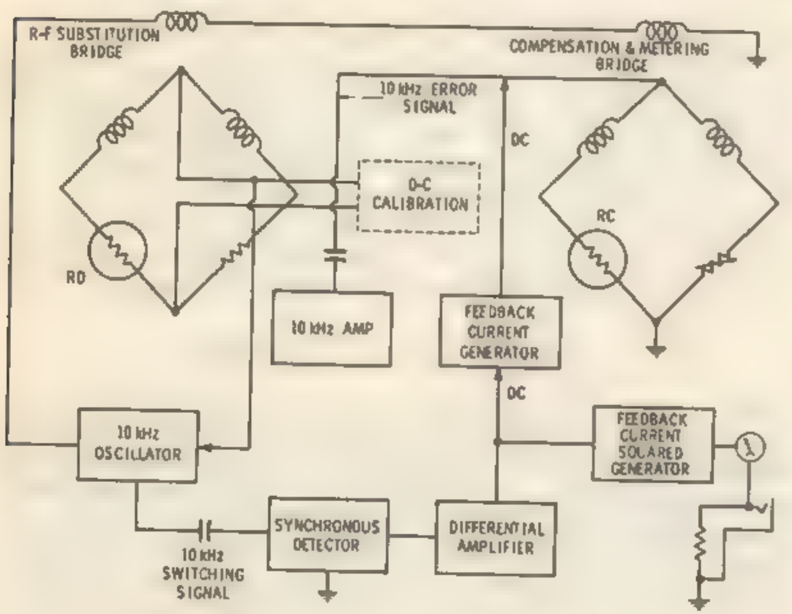
Fig. 10-1. Typical bolometer bridge circuit.

coaxial or wave guide. Such devices, appropriately termed bolometer mounts, allow a "bias" connection to the bolometer element, as well as a proper entry point for r-f. The bolometer is connected as one leg of a Wheatstone bridge (or some modification thereof) through the bias connection, and bridge excitation is applied. (See Fig. 10-1.) The d-c or low-frequency a-c bridge excitation serves as the bolometer-element bias power which affects the bolometer's resistance, so that the bridge is essentially balanced. When the unknown r-f power is applied to the bolometer, the resulting temperature rise causes the element's resistance to change, tending to unbalance the bridge. By withdrawing a like amount of d-c or a-c bias power from the element, the bridge may be returned to balance, and the amount of bias power removed can be measured and displayed on an indicating meter.

AUTOMATIC BOLOMETER BRIDGES

There are a number of bolometer bridge designs which provide degrees of accuracy, speed, and convenience. Since all bolometer elements are temperature-sensing devices, they are, in themselves, unable to distinguish between applied power-level changes and environmental temperature changes. As bolometer bridge sensitivity is increased, even minute temperature variations appear as though a varying power were being applied to the bolometer element. The result, if not compensated for, is "zero drift" of the power meter and erroneous power measurements.

A dual bridge arrangement, as shown in Fig. 10-2, is used to compensate for variations in temperature at the thermistor mount. The thermistor mounts have two thermistor elements,



Courtesy Hewlett-Packard Co.

Fig. 10-2. A dual bolometer bridge arrangement.

one for sensing ambient applied power (R_d) and one for sensing ambient temperature (R_c). Each element is connected to its own bridge circuit in the meter, which automatically controls bias power (10 kHz). The two elements are in close thermal proxmity, but R_c is isolated from the applied r-f power.

This arrangement compensates for temperature changes, thus reducing zero drift. Another advantage of this design is that when zeroed on the most sensitive range, the meter may be switched to any other power range without rezeroing. This type of meter provides a d-c output that is proportional to the microwave power measured. Such an output is useful for recording purposes or for control of external circuits.

CALORIMETRIC POWER METERS

Bolometer elements cannot be used for direct power measurements at levels above 10 to 50 milliwatts because of their physical size. Calibrated directional couplers or attenuators are sometimes used to reduce the power level to the bolometer's range. However, this also reduces the overall accuracy because of the additional tolerances on coupling factor or attenuator calibration. Where better accuracy is desired, calorimetric techniques provide a more useful result.

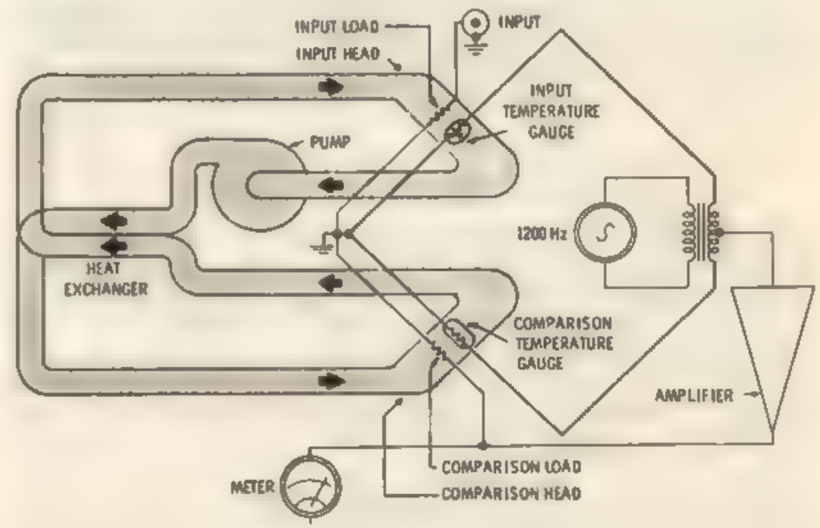


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Fig. 10-3. A bridge-type calorimeter.

Calorimetric power meters dissipate the unknown power in a resistive termination which is matched to the transmission line or source impedance. The temperature rise caused by the power dissipation is then measured by a temperature sensor which is calibrated against known amounts of d-c power. Cal-

orimetric power meters fall into two categories: dry and fluid. Dry calorimeters depend on a static thermal path between the dissipative load or resistor and the temperature sensor. Such a thermal path can be supplied by a heat sink. This arrangement often requires several minutes for the termination and sensor to reach equilibrium, making measurements time-consuming and too sluggish for tuning optimum performance.

Fluid calorimeters such as shown in Fig. 10-3 use a moving stream of oil to transfer heat quickly to the sensing element. An amplifier-feedback arrangement, in conjunction with the series oil-flow system, reduces measurement time to a few seconds (usually less than five seconds) for full-scale response. The physical size of the termination and the flow rate of the liquid passing over the termination are primary factors which determine the maximum power that may be dissipated by a fluid calorimeter.

THERMOCOUPLE METERS

A thermocouple consists of two dissimilar metals physically joined together. When heat is applied to the junction point, the metals generate electrical current. Thermocouples can be used

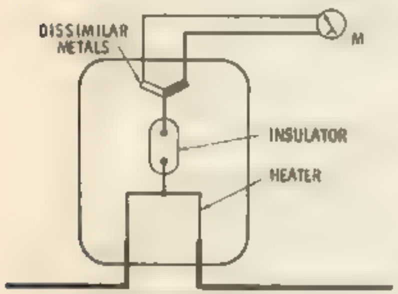


Fig. 10-4. Basic thermocouple power-meter circuit.

to measure power at high frequencies. This is done by placing the junction point within the r-f energy field and monitoring the resultant voltage on a sensitive d-c voltmeter. Often, thermocouples are placed in a vacuum so that a slight amount of heat will produce a measureable current. As shown in Fig. 10-4, the heater portion of the thermocouple forms one of the conductors in an r-f transmission line. Heat produced by uhf currents passing along the transmission line is applied to the junction of the two thermocouple metals. The resultant voltage is monitored by a d-c voltmeter. Thermocouples have the ad-

vantage that they can be calibrated by low-frequency signals, even direct current in some cases, but will retain their calibration at high frequencies. However, because of their physical construction, they tend to disrupt the impedance in the transmission line, especially at the higher frequencies. This creates standing waves, loss of power, and other problems.

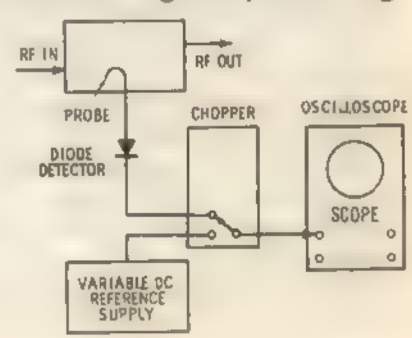
DIODE PROBES

Diode probes are used for various uhf and microwave tests, including power meters. A diode probe is nothing more than a diode connected to a pickup probe, as described in Chapter 6. While it is possible to use a vacuum tube as a diode, a crystal diode is smaller and needs no heater supply. No matter whether tubes or crystal diodes are used, their function is to convert r-f power into d-c voltage. This voltage can then be monitored with a d-c voltmeter, and calibrated in terms of power or whatever other value is desired. Diode probes are often used with vtvm equipment. When used for uhf work, they must be designed to provide minimum capacitance and maximum input resistance. A high capacitance could produce considerable capacitive reactance in a uhf circuit. On the other hand, maximum input resistance keeps the current at an absolute minimum.

PEAK-POWER MEASUREMENT

A frequent requirement in microwave work is the measurement of peak power of a periodic pulse. This may be done by various indirect techniques, using bolometers or calorimeters. It is also possible to use a diode probe in a video comparator circuit to bring a known d-c voltage in a known impedance to a level which is equal to the pulse being measured. In a practical peak-power calibrator, as shown in Fig. 10-5, the r-f sig-

Fig. 10-5. Basic diode probe power-meter circuit.



nal is applied to the input circuit which, through a power splitter or attenuator, feeds the diode detector. The demodulated diode output and the output of a d-c reference supply are simultaneously fed to the video output through a mechanical chopper. In making a measurement, a suitable external oscilloscope is connected to the video output, and the d-c reference voltage is adjusted so that it is exactly equal to the peak value of the demodulated pulse. The level of the required d-c reference voltage is then indicated on the panel meter, calibrated to read peak r-f power.

DUMMY LOADS

A dummy load is used to prevent the radiation of power which could cause interference. Dummy loads are required for service and test procedures on uhf equipment, as they are for lower-frequency units. However, a uhf or microwave dummy load must be of special design so as not to create standing waves. A conventional wire wound resistor, for example, will create a high inductive reactance at ultrahigh frequencies. This reactance will cause a severe mismatch between the line and the dummy load, resulting in standing waves, power loss, etc. If such a dummy load were connected directly to a uhf transmitter output, it might even affect the transmitter tuning. At the normal operating frequency, a uhf antenna is almost pure resistance. The dummy load that replaces such an antenna must also present almost pure resistance, with an absolute minimum of inductive reactance.

MICROWAVE MEASURING TECHNIQUES

There are two basic types of microwave measuring techniques: fixed frequency and swept frequency.

Fixed-frequency techniques offer the highest precision attainable for individual measurements, because the small inherent mismatch errors which must be tolerated on a broad frequency-sweep basis may be individually tuned out. Consequently, fixed-frequency techniques are widely used in "standards" measurements and in applications where the system under test is operating either at a single frequency or within a very narrow band. The slotted-line technique of impedance and standing-wave ratio measurements is typical of the fixed-frequency tests.

Swept-frequency techniques are used to obtain measurements quickly and easily over a range of frequencies. Important parameters such as swr, directivity, attenuation, noise figure, etc., can be determined on a swept-frequency basis, and the user can quickly determine whether there is a narrow-band phenomenon, such as a resonance, in the device being tested. The swept-frequency technique of standing-wave ratio measurement and of attenuation measurement are typical of the sweep-frequency tests.

SLOTTED-LINE MEASUREMENTS

Impedance matching a load to its source is one of the most important considerations in microwave and uhf transmission systems. If the load and source are mismatched, part of the power will be reflected back along the transmission line toward the source. This reflection not only prevents maximum power transfer, but also can be responsible for erroneous measurements of parameters, and even cause circuit damage in high-power applications. The power reflected from the load interferes with the incident (forward) power, causing standing waves of voltage and current along the line. The ratio of standing-wave maximums to minimums is directly related to the impedance mismatch of the load. The standing-wave ratio therefore provides a valuable means of determining impedance and mismatch.

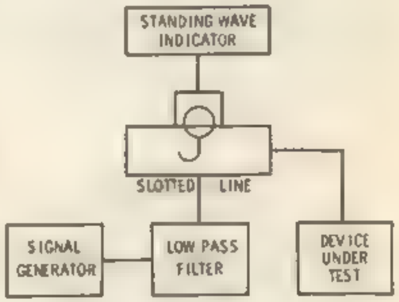


Fig. 10-6. Basic slotted-line test setup.

Standing-wave ratio can be measured directly at fixed frequencies using a slotted line. The basic slotted line is a section of coax transmission line or wave guide with a probe and diode detector which can be moved along the line. Usually, the only control on a slotted line is a dial that moves the probe and diode along the line. On other slotted lines, the probe (a form of stub) can be tuned by a knob that changes its length. Also, the amount of energy extracted by the probe can be varied by a control that determines the distance or depth of the probe within the line.

In use, the slotted line is placed immediately ahead of the load, as shown in Fig. 10-6, and the source is adjusted for some fixed amplitude-modulation frequency (usually 1 kHz) at the desired microwave frequency. The slotted-line probe is loosely coupled to the r-f field in the line, thus sensing relative amplitudes of the standing-wave pattern as the probe is moved along the line. The ratio of maximum to minimum swr is then read directly on the standing-wave indicator.

Because the probe must not be allowed to extract any appreciable power from the line, high sensitivity and low noise are required in the detector and indicator. To this end, the indicator is sharply tuned to the modulation frequency of the source, thereby reducing noise and allowing the use of a high-gain audio amplifier and voltmeter circuit.

Other considerations relative to accurate slotted-line measurements include elimination of harmonics from the source prior to entering the slotted line, low frequency modulation in the source, and low residual standing-wave ratio in the slotted line itself.

REFLECTOMETER TECHNIQUES

The reflection coefficient (ρ) of a device or system is another useful term in establishing the impedance match of microwave and uhf devices. The amplitude of reflected voltage with respect to the incident voltage is given in terms of db *return loss*

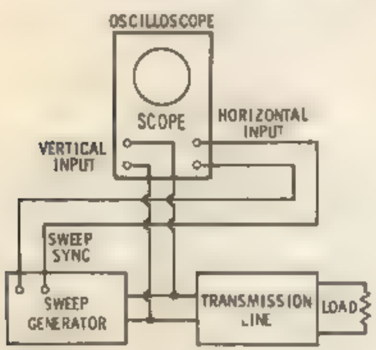


Fig. 10-7. Basic swept-frequency reflectometer circuit.

by the expression: $db = -20 \log_{10} \rho$. For example, if the reflected signal from a test device is 26 db below the incident-signal level, the reflection coefficient of the device is calculated at 0.05. In a like manner, any reflection coefficient from zero to one can be determined by a measure of the return loss.

Present-day reflectometer techniques make use of sweep-frequency signals rather than fixed-frequency signals. The basic swept-frequency reflectometer circuit is shown in Fig. 10-7. The sweep-generator output is connected to the transmission line and to the vertical-deflection circuits of an oscilloscope. The horizontal sweep of the oscilloscope is synchronized with the signal-generator sweep. Therefore, the vertical deflection on the oscilloscope is determined by the power at the source end of the line, and any point along the trace corresponds to a given frequency. Several types of measurements can be made. For example, the transmission line can be terminated in its own impedance, and the oscilloscope pattern checked. If the pattern is flat across the entire frequency range, the match between transmission line and load will be perfect. Variations in amplitude on the pattern indicate that there are standing waves on the line and that part of the energy is being reflected, which is a result of mismatch.

TYPICAL SWEPT-FREQUENCY SWR MEASUREMENT

The basic setup for making swept-frequency swr measurements is shown in Fig. 10-8. In this circuit, an X-Y recorder is used instead of an oscilloscope. It provides a permanent record on chart paper instead of an oscilloscope display. A portion of the sweep-generator output signal is removed by the directional coupler and fed back to the power-output level-control

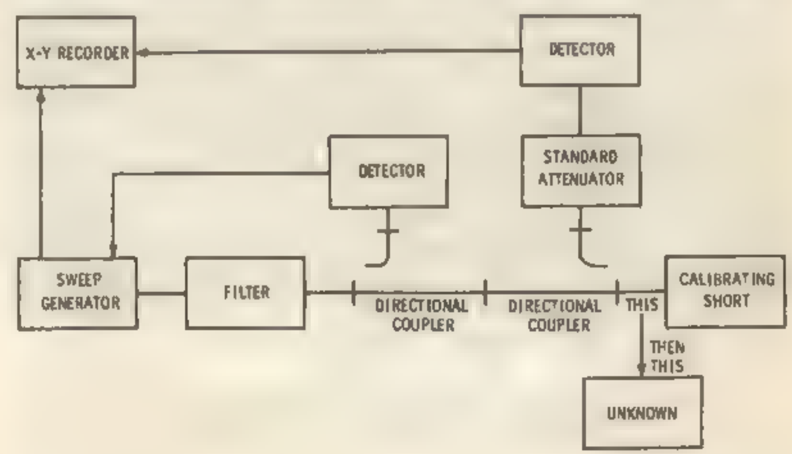


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Fig. 10-8. Swept-frequency swr measurement setup.

circuits of the sweep generator. This closed loop provides a means of maintaining the sweep-generator output constant. Any variation in sweep-generator output amplitude at any point along the sweep-frequency range will cause an error.

The system is first calibrated by placing a short in the output port, thus reflecting all of the incident power. The detector in the reverse-arm coupler samples the reflected power and pro-

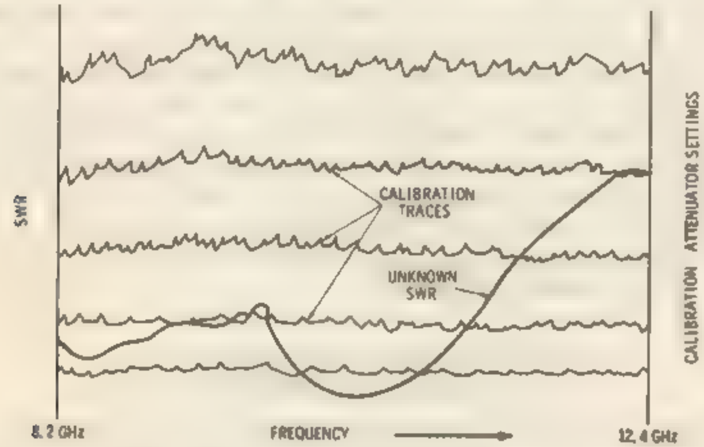

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Fig. 10-9. Typical X-Y recorder swr plot.

vides a proportional d-c voltage for readout. By placing a calibrated attenuator ahead of the detector, specific amounts of return loss may be preinserted for calibrating the X-Y recorder. The attenuator is set for the expected return loss, and the recorder is set to a range that will display that loss figure. The attenuator is then returned to zero, the short is removed, and the device to be tested is connected in place of the short.

Any reflected signals will then be detected and the value displayed on the X-Y recorder. If the circuit is properly calibrated, the X-Y recorder trace will represent the standing-wave ratio of the device under test over the sweep-frequency range. In theory, a perfectly matched impedance would produce a perfectly flat trace, indicating a 1:1 ratio. A typical swr plot on an X-Y recorder is shown in Fig. 10-9.

TYPICAL SWEPT-FREQUENCY ATTENUATOR MEASUREMENT

The basic setup for making swept-frequency attenuator measurements is shown in Fig. 10-10. Again, an X-Y recorder and

an automatic leveling for sweep-generator power output is used. However, the directional coupler is now arranged so that the reflected channel in the previous swr measurement becomes the transmission channel.

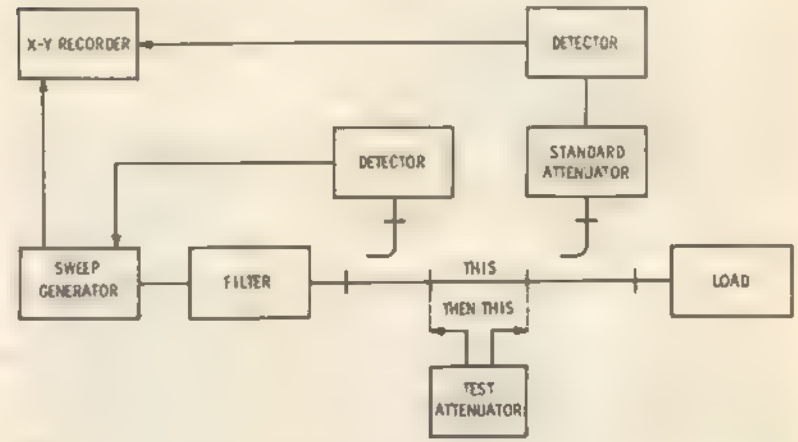

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Fig. 10-10. Swept-frequency attenuator measurement setup.

The system is first calibrated by placing a length of loss-free transmission line between the source and detector. A reading is obtained on the X-Y recorder with the section of loss-free line in the circuit. By adjusting the calibrated attenuator ahead of the detector, specific amounts of loss can be preinserted for calibration of the X-Y recorder. The detector attenuator is set for the expected loss, and the X-Y recorder is set to a range that will display that loss figure. The attenuator is then returned to zero, the loss-free line is removed, and the attenuator to be tested is connected in place of the loss-free line.

The resultant signal will then be detected and the value displayed on the X-Y recorder. If the circuit is properly calibrated, the X-Y recorder trace will represent the insertion loss of the attenuator under test over the sweep-frequency range.

LECHER LINES

Lecher lines are used in experimental uhf work primarily to measure wavelengths or to use the principles of an r-f line. A typical Lecher line is simply a two-wire line with a sliding shorting bar across the two lines. For experimental purposes,

the line is provided with a pickup coil and indicator (often a lamp) placed near the generator or source end of the line. (See Fig. 10-11.) In use, the line is fed from a signal source, and the shorting bar is moved to a desired wavelength.

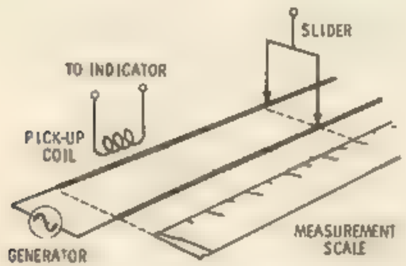

Fig. 10-11. Lecher line.

A typical use for a Lecher line is the measurement of generator frequency. The shorting bar is moved until the line becomes resonant at the generator frequency, as indicated by the pickup-coil lamp or other indicator. The actual wavelength can be measured, and the frequency calculated from this measurement.

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UNDERSTANDING UHF EQUIPMENT

by John D. Lenk

Encountering ultrahigh-frequency equipment for the first time can be a bewildering experience for the student or beginning technician. After having acquainted himself somewhat with the "normal" electronic gear and components used at lower frequencies, he is suddenly confronted with such an array of "plumbing" and other seemingly nonelectronic paraphernalia that he truly finds himself in a quandary. Nothing seems recognizable for what it really is! This book should prove to be most valuable for those who find themselves in such a state of confusion.

The first chapter contains answers, presented in a brief and straightforward manner, to a series of questions most often asked of instructors in the uhf field. Other chapters contain detailed information on specific items of uhf components, circuits, and equipment. Throughout the book, emphasis is placed on fundamentals and basic features. In addition, comparisons between uhf and lower-frequency equipment are given so that the exact function of uhf components and circuits can be more easily understood.

In the last chapter, specific items of test equipment and various techniques that are unique to uhf and microwave operation are described and illustrated.

ABOUT THE AUTHOR

John D. Lenk has been a full-time writer since 1949. His numerous books and technical articles have found wide acceptance. In addition, he is a technical writer for industry. His background includes electronics training in the U.S. Navy during World War II. He has held a First-Class Radiotelephone Licence and an Amateur Radio Licence since 1939. Other popular FOULSHAM-SAMS books by Mr. Lenk include: *Servicing With Dip Meters, Electronic Corrosion Control for Boats, Direct Readout Meters, Applications Handbook for Electrical Connectors,* and *Understanding Telemetry Circuits.*

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